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CABINETS AND COLLECTIONS. Natural history cabinets and collections took shape in two forms during the Renaissance: the cabinet of curiosities and the botanical garden. The cabinet of curiosities, or *Wunderkammer,* was a repository of objects noteworthy to the Renaissance philosopher: rarities, exotica (from Asia or the New World), monstrosities, artifacts, natural objects, and items of historical interest. The great Renaissance collectors included Ulisse Aldrovandi, whose museum (which he bequeathed to the city of Bologna), or *teatro* or *microcosmo,* as he variously termed it, contained a dragon; and the German Jesuit Athanasius Kircher, whose collection in Rome reflected not only his interests in natural philosophy but also in Egyptian hieroglyphics. Owners restricted access to a discriminating (and carefully chosen) public of fellow scholars and aristocratic or clerical patrons. Aldrovandi kept a ledger of visitors, among them one pope, six princes, twenty-one professors, eighty-seven doctors, six painters, and a notary. Although a few noblewomen visited his museum, they were not enumerated in the roll.

The physical composition and arrangement of an early modern cabinet of curiosities was an idiosyncrasy of its owner. In general, no clear differentiation could be made between objects displayed and the means of display, as cupboards, shelves, drawers, mountings, and frames—the ceiling also served for and as display—were splendid objects in themselves, fully integrated with their contents. Within the room or rooms, objects followed one another according to the three kingdoms of nature: animal, vegetable, and mineral; the importance to collectors of objects like cameos and worked baroque pearls made the boundaries between the artificial and the natural relatively porous and unmeaning.

Besides the splendid display of material objects, the cabinet had another dimension: the catalog, which ordered and described its contents in a form portable beyond its walls. The Dutch merchant and manufacturer Levinus Vincent, whose cabinet had been visited by Peter the Great and Carlos III of Spain, published in 1719 a splendid catalog depicting and describing his holdings. The collection of the Italian antiquary Cassiano dal Pozzo consisted entirely of representations rather than objects: over seven thousand drawings of classical and medieval antiquities, fossils, and botanical, zoological, and horticultural subjects. Several theoreticians of collecting, including the German Samuel Quiccheberg, in his *Inscriptiones vel tituli theatri amplissimi* (1565), discussed the relation of the material cabinet and the idealized catalog.

Botanical gardens began in sixteenth-century Italy as adjuncts to the teaching of medicine and evolved into collections not just of plants useful in *materia medica* but of botanical diversity in general. Over time they developed into repositories of botanical diversity for its own sake. By the mid-eighteenth century the garden was paired with the herbarium, another of the great genres of modern collecting. Botanical gardens through the eighteenth century were laid out almost exclusively along medical or taxonomic lines (according, for example, to the system of Joseph Pitton de Tournefort, Bernard de Jussieu, or Carl Linnaeus), with little concession to horticultural (rather than architectural) aesthetics. All the earliest gardens (in Padua, Pisa, Leyden, Oxford, and Montpellier) and most later ones were associated with universities, although governments maintained some (the Jardin du Roi, later Jardin des Plantes, Paris) and private individuals others (George Clifford, Holland). In all cases, they restricted admission, generally to students and well-to-do patrons.

From the early eighteenth century, the contents of collections and their administration became ever more standardized. To return to botany, herbarium sheets of the seventeenth and early eighteenth centuries containing pressed and dried plant specimens were often ornamented—dried plants spilling from engraved flowerpots, for example—and had no standard size. Each collector's system of preparation, labeling, sorting, and storage was unique. The growth of networks of botanical collectors and systematists and of widely shared taxonomic systems fostered standardization in the second half of the eighteenth century. The most important botanical authority, Linnaeus, succeeded in imposing his standard size folio herbarium sheet on most of his correspondents, and he ruthlessly cut down sheets he received to the size of his own cupboards, heedless of ornament or aesthetics. At the same time, administrative techniques drawn from commerce and government regulated the contents of collections and kept track of exchanges and purchases among them. The eighteenth century also saw the purchase and transfer of whole collections, like Sir Hans Sloane's assortment of natural objects and antiquarian and ethnological material, bought by the British government in 1753, and Linnaeus's herbarium, sold to J. E. Smith of London in 1784. The first collection formed the core of the British Museum; the second ended up in the Linnean Society, founded in 1788. This new genre of collection, systematic rather than aesthetic, transferable, and increasingly standardized, had almost completely supplanted the cabinet of curiosities by the turn of the nineteenth century. Even amateur collectors of seashells, plants, birds' eggs, and other hobbyists came to order their collections along scientific lines, labeled according to the latest systematics and stored out of sight in boxes, cases, and cupboards analogous to those used in scientific institutions and university collections.

The nineteenth century opened a new era in the typology of collections, still recognizable today and marked by differentiation into three genres: systematic, applied, and aesthetic and didactic. The work of classifying the world's plants and animals begun in the Renaissance went on, but it did so behind the scenes, in herbaria and zoological museums open only to accredited scholars and invisible to the public. The institutions housing this work—Kew Gardens near London, the Jardin des Plantes and Muséum d'Histoire Naturelle in Paris, the Schönbrunn Gardens in Vienna, and later their colonial satellites in India, Java, Mauritius, Jamaica, and elsewhere—also carried out imperial schemes of acclimatization, hybridization, and plant and animal transplantation. This work was linked to surveys important for systematics and provided revenues both for the gardens and their overseeing governments. Finally, as part of larger nineteenth-century movements for public health, education, and recreation, these institutions came to serve as teaching establishments and places of entertainment for an ever-widening general public.

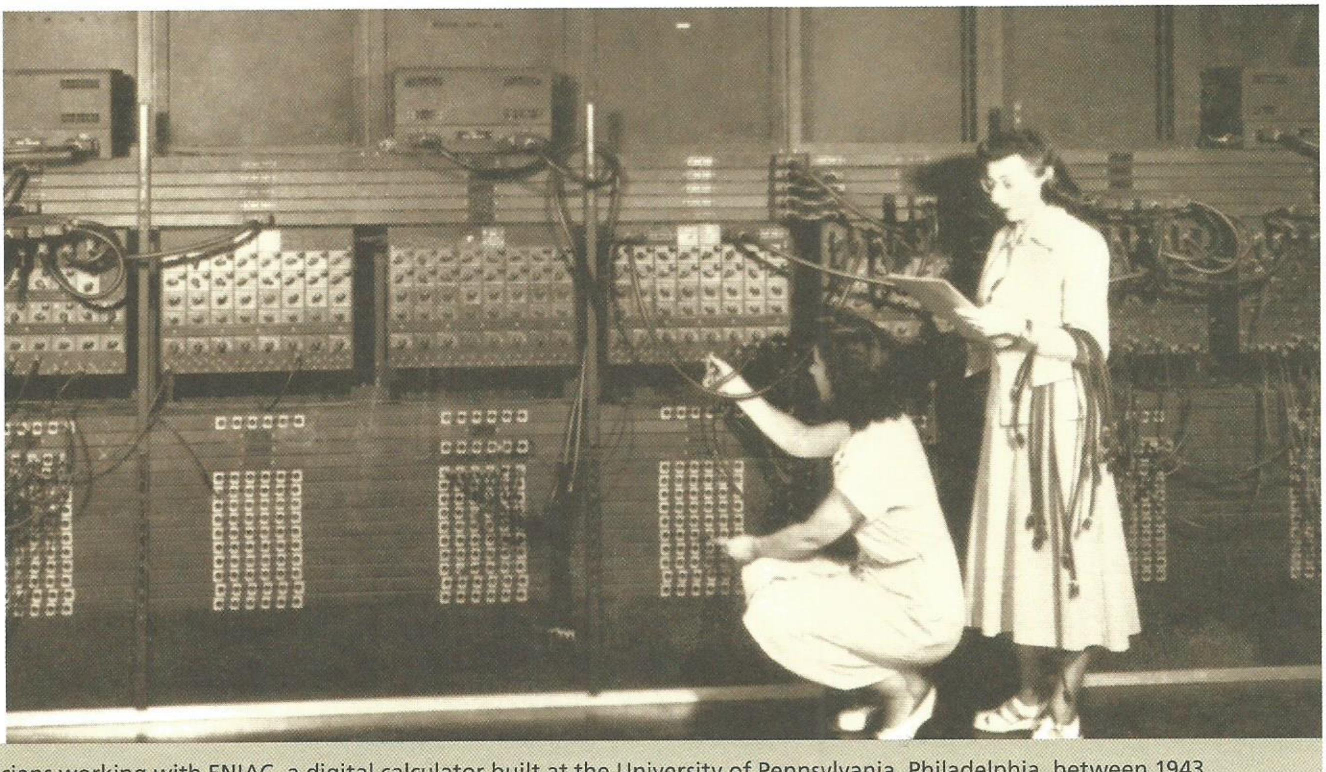
Parallel to the enclosure of the herbarium as a de-aestheticized, private, and academic space was the opening of the botanical garden as a public park. This theoretical reconception accompanied a shift from the rigidly rectilinear garden plans of the seventeenth and eighteenth centuries taking taxonomy as their planting principle, to more openly aesthetic designs drawing on the picturesque eighteenth- and nineteenth-century English landscape style and organized by geographical or climatic constellations of flora. Guidebooks, identifying labels, and public lectures furthered the education of visitors. Likewise, modern zoological gardens, with their combination of the spectacular and the educational, taking their cue from the zoo founded in Regent's Park, London, in 1828, served an important didactic and recreational function in major European cities. Within doors, the nineteenth century's great museums likewise split their functions between public spectacle and instruction—competing in this in the later part of the century with the great exhibitions—and restricted scholarly collections.

In the twentieth century, this tripartite division continued to hold despite profound changes: transformations in biological theory and systematics (particularly the theory of evolution); political shifts (especially the collapse of the European empires, which altered the context of agricultural interventions); and changing fashions in pedagogical theory and museum display. The modern herbarium, zoo, and science museum would be quite recognizable to a visitor from the mid-nineteenth century, whereas the early modern collector of curiosities would be baffled in spaces epistemologically so foreign. Nevertheless, some new features and types of collections came into existence in the twentieth century. The rise of ecology and conservation biology have led to a return to the collection of biological (and ethnological) diversity for its own sake, reminiscent of the catchall collecting of the sixteenth and seventeenth centuries. The computer has increasingly made information the object of collection, in public media and forums like the World Wide Web. These collections include the genomes of fruit flies, *Arabidopsis,* and human beings, and the widely accessible electronic catalogs of great libraries, themselves collected into metacatalogs like the Karlsruher Virtueller Katalog (http://www.ubka.uni-karlsruhe.de/hylib/virtueller_katalog.html).

A. J. Lustig

CALCULATOR. Although calculation had long been a part of the daily routine of commercial life, it was two natural philosophers of the seventeenth century, Blaise Pascal and Gottfried Leibniz, who invented the first machines that could carry out arithmetic processes automatically. Pascal's could add and subtract; Leibniz's did well at addition and multiplication. Although considered mechanical marvels, these devices had little immediate impact on the way people did arithmetic. Of greater practical importance was John Napier's discovery of logarithms, which made it possible to multiply or divide by addition or subtraction. The properties of logarithms were embodied in the slide rule, which soon found use in calculations relating to taxation and, during the nineteenth century, in all sorts of problems considered by scientists and engineers.

In the second half of the nineteenth century, machines that could carry out arithmetic operations came into use in commerce. The most successful of them did addition best. A few—notably the Swiss-made Millionaire—could multiply



Technicians working with ENIAC, a digital calculator built at the University of Pennsylvania, Philadelphia, between 1943 and 1946. The women are rewiring the "program." The US Army paid for ENIAC (Electronic Numeric Integrator and Calculator) to facilitate ballistic computations.

directly rather than by repeated addition, and were of particular use to scientists. Observatories and laboratories hired people called computers to do routine calculations by hand, using published mathematical tables, and by machine.

Nineteenth-century scientists and mathematicians had little to do with the invention of calculating machines. They took a more active role in the development of difference engines, machines that computed values of functions using the method of finite differences. Charles Babbage envisioned and Georg and Edvard Scheutz successfully built a difference engine. One Scheutz difference engine was used briefly at the Dudley Observatory in Albany, New York.

Instruments for carrying out more complex mathematical operations also received the attention of scholars. In 1855 James Clerk Maxwell invented a form of planimeter, a device for finding the area bounded by a closed curve. Planimeters had applications to many scientific and engineering problems, for example, finding the work done by a steam engine from an indicator diagram. In 1876 William Thomson, Lord Kelvin, proposed an instrument for representing a curve as the sum of terms in a harmonic series. The British long used Kelvin's harmonic analyzer and its descendants to predict the tides. Kelvin's instrument inspired several imitators, such as the predictor, designed by William Ferrel of the U.S. Coast and Geodetic Survey in 1880. Larger versions of this machine operated in the U.S. into the 1960s.

In the 1930s, Vannevar Bush at the Massachusetts Institute of Technology developed a much more complex, room-sized mechanical device for solving differential equations. To use Bush's differential analyzer, as well as similar instruments built in Great Britain and Norway, the operator had first to assemble an array of gears, shafts, disk integrators, and electric motors and to enter data by tracing a curve on an input table. The result appeared as a curve on an output table.

During the 1920s and 1930s, punched card equipment, initially developed for census tabulation and then applied to accounting work, came into the social sciences and astronomy. Centers devoted to computation developed at government agencies and universities, particularly Columbia in New York City and Iowa State in Ames. In the late 1930s, a physics graduate student at Harvard University, Howard Aiken, conceived a calculator that could be programmed to carry out calculations. With the help of Harvard faculty, he persuaded International Business Machines (IBM), the most successful maker of punched card equipment, to build the calculator and donate it to Harvard. The machine, called the Automatic Sequence Controlled Calculator, or Mark I, calculated for the U.S. Navy when completed during World War II. As with IBM accounting equipment, calculations were carried out using electromechanical relays. Germany also built relay calculators. During the same period, physicist John Mauchly and engineer J. Presper Eckert designed and built the first general purpose electronic computer, the ENIAC, at the University of Pennsylvania. All of these machines filled a room.

By the 1960s, the introduction of smaller, more reliable electronic components made it possible to make electronic calculators that fit on a desktop. Those introduced by the British firm of Sumlock Comptometer and sold under the name "Anita" used vacuum tubes. In 1964, Sony exhibited a prototype transistorized calculator at the New York World's Fair. Sony and other companies, such as Sharp and Wang Laboratories, soon were selling desktop electronic devices. They cost several thousand dollars, but numerous scientists used them.

In the 1970s, the introduction of the integrated circuit made it possible to build still smaller, hand-held electronic calculators. These initially cost several hundred dollars, but the price quickly fell. The hand-held calculator soon displaced the slide rule and many printed tables. Some early electronic calculators could only do business arithmetic. Others, intended for scientists and engineers, could compute trigonometric functions, exponents, and statistical functions. Early makers of hand-held calculators included the Japanese firm of Busicom and such American companies as Texas Instruments and Hewlett Packard.

As integrated circuits became more powerful, so did calculators. In the mid-1980s the Japanese firm Casio introduced a hand-held calculator that could graph simple functions. Hewlett Packard, Texas Instruments, and other companies soon followed suit; graphing calculators are now widely used in the classroom as well as the laboratory. The more expensive forms of these machines can do symbolic manipulations—not only simple algebra, but also calculus. The programs used in these calculators rely heavily on the results of university mathematicians and scientists, but the devices themselves, like nineteenth-century calculating machines, are very much commercial products.

PEGGY ALDRICH KIDWELL

CANCER RESEARCH. At the end of the nineteenth century, little was known about the causes of cancer, but the prospects for learning more appeared to be brightening with the emergence of evidence that at least some cancers might be produced by infectious microorganisms. Scientists in many laboratories searched for such cancer-causing agents without success until 1909, when a farmer brought Peyton Rous, a young biologist on the staff of the Rockefeller Institute for Medical Research, a chicken with a large sarcoma-type tumor protruding from its right breast. Rous obtained a cell-free extract from the tumor by mincing and then filtering the tissue. He then injected a solution of the extract into healthy chickens of the same breed and found that they, too, developed sarcomas. Rous contended that the tumors might have been stimulated by a "minute parasitic organism" carried in the extract—perhaps a virus.

Other scientists using Rous's methods failed to induce tumors in mice, rats, rabbits, or dogs. By the 1930s the theory that viruses cause cancers had fallen into deep disrepute. John Bittner, a biologist at the Jackson Laboratory in Bar Harbor, Maine, found that a tendency to breast cancer in certain strains of mice could be transmitted from mothers to foster children—that is, independently of the animals' genetic makeup. Bittner suspected that the mothers transmitted a virus to the infant mice when they suckled. Reluctant to challenge the prevailing antiviral paradigm of oncogenesis, he called the agent involved a "milk factor." His suspicion was later validated by recognition of the mouse mammary tumor virus (MMTV).

In the scientific community at large, theories of viral oncogenesis were revived by Ludwik Gross, a refugee from Poland who joined the staff of the Veterans Hospital in the Bronx. In 1944, Gross began injecting healthy mice with an extract obtained from ground-up organs of adult leukemic ones. He failed to induce leukemia in the recipient mice until, probably in 1949, he tried injecting the extract into newborn mice. They all developed the disease within two weeks. In the 1950s, scientists in America and Europe obtained filtrates from a large variety of tumors, injected them into newborn mice, and isolated an abundance of viruses that provoked tumors in many species, including hamsters, rats, apes, and cats. By the early 1960s, animal

Oncogenes influence the mutation, amplification, and proliferation of cancer cells. Here a fission protein (in green), created by abnormal positioning of DNA strands from different chromosomes, initiates the production of oncogenes.

tumor virology had become a major branch of basic medical and biological science. In 1966, at the age of eighty-five, Rous shared the Nobel Prize in physiology or medicine.

Knowledge that viruses are DNA or RNA wrapped in a protein coat allowed tumor virologists to begin reaching into the mystery of what occurs when a virus transforms a normal cell into a cancerous one. In the early 1960s, Renato Dulbecco, at the Salk Institute in La Jolla, California, demonstrated that when a virus invades a cell, its genetic material is incorporated into the cell's native DNA, with the result that it perverts the cell's machinery of regulated growth, and causes it to multiply malignantly. Dulbecco worked with DNA viruses. But Howard Temin, a former student of Dulbecco now at the University of Wisconsin, ran into difficulties pursuing a similar line of research using the Rous sarcoma virus, whose genetic material is RNA. RNA is synthesized using the code that DNA contains, but according to the then-prevailing central dogma in molecular biology, it could not generate DNA and, hence, could not integrate its genetic information into the DNA of a cell.

Temin contended that the central dogma must at least in part be wrong, that Rous viral RNA somehow generated DNA complementary to itself that could integrate into the DNA of the cell. Although ridiculed for his claim, Temin pursued it experimentally through the 1960s, focusing on showing that such integration occurred. In 1969 he turned to a consideration of how the virus's RNA could be physically made into complementary DNA. In 1970, he found the answer—an enzyme that catalyzes the synthesis of DNA from RNA.

The same discovery was made simultaneously and independently by David Baltimore, a member of the MIT faculty who since his graduate-school days had been working on the genetic systems of RNA viruses. In 1970, Temin and Baltimore reported, in separate, back-to-back articles published in *Nature,* the discovery of the enzyme, promptly dubbed "reverse transcriptase" in recognition of its ability to transcribe RNA back into DNA. At the end of his paper announcing the enzyme, Temin noted that the light it cast on how retroviruses reproduce raised "strong implications for theories of viral carcinogenesis."

No virus had been shown to cause cancer in human beings, but the rapid development of tumor virology had convinced a coalition of scientists and influential laypeople to agitate for a stepped-up federal cancer program. In 1971, the agitation yielded the National Cancer Act, inaugurating a "War on Cancer" that would more than triple the budget of the National Cancer Institute by 1976. Biomedical scientists managed to divert resources from the war to research into the interaction of tumor viruses with the cell. They argued that victory over cancer would come not with searching for human tumor viruses but from understanding how the integration of a virus's genetic information into a cell's DNA transformed the cell into a source of malignancy.

In 1969, the biologists Robert J. Huebner and George J. Todaro, addressing the transformation puzzle, theorized that the cells of many, if not all vertebrates must naturally contain two kinds of cancer-related DNA: "virogenes," to create RNA viruses, and "oncogenes," a term they coined to denote genes with the power to transform normal cells into tumor cells. They speculated that both genetic substances lie latent in the cell, having entered it by some ancient infection, until activated by natural causes or environmental carcinogens.

In the early 1970s, J. Michael Bishop and Harold E. Varmus, both young faculty members of the medical school of the University of California in San Francisco, began investigating the virogene/oncogene hypothesis. They sought to determine whether any stretch of DNA in a normal chicken cell resembles the Rous virus's transforming gene, a tentative identification of which had recently been established by several other scientists in the San Francisco area. Bishop and Varmus dubbed the transforming viral RNA the "sarc" gene and sought to determine whether the viral "sarc" gene has a cousin—scientists call it a homologue—in the DNA of a normal chicken.

Between 1976 and 1978, the Bishop-Varmus group found that the viral "sarc" fragment is homologous not only to a region in the DNA of chickens but also to regions in the DNA of quail, turkeys, ducks, emus, calves, mice, and salmon. They even had detected evidence of them in human DNA. "Sarc" seemed to have cousins in DNA everywhere. The "sarc" homologues were obviously not the oncogenes—the latent oncogenic DNA—that Huebner and Todaro had originally proposed. Evolutionary reasoning helped identify them. The major groups of species—birds, mammals, and fish—that carry the "sarc" cousins had separated at least 400 million years earlier. To Bishop and Varmus, the plain evidence that the "sarc" homologues had been conserved through so much time and speciation indicated that they might be involved in some critical cellular function such as growth and development. They appeared to be normal genes that can be turned into oncogenes by viral action or by a physical or chemical agent.

In 1979, the laboratory of Robert Allan Weinberg at MIT reported that normal cellular DNA could indeed be transformed into oncogenic DNA with a chemical carcinogen. Soon, experiments in other laboratories detected transformed DNA—DNA changed from that of a normal cellular gene—in a variety of cancer cells, including carcinomas taken from rabbits, rats, mice, and people. Most of these cellular genes seem to exist all over the tree of animal evolution, just like the cousins to the viral "sarc" gene (now designated *src*, in conformity with the classical rules of three-letter genetic nomenclature). Like the *src* gene, these other cellular genes probably have a role in the fundamental cellular processes of growth, regulation, and differentiation. They are thus normal cellular genes that can be turned into oncogenes by chance processes within the cell as well as by environmental carcinogens, including tobacco smoke. These "proto-oncogenes"—potential agents of cancer—comprise, as Bishop has said, a kind of "enemy within."

The multiple steps that led to the discovery of oncogenes revolutionized cancer research and widened opportunities for the study of normal cell growth and regulation. Parts of the work earned Nobel Prizes, including one, in 1975, for Dulbecco, Baltimore, and Temin and another, in 1989, for Bishop and Varmus. Coupled with increasing knowledge of the oncogenic role of environmental carcinogens, the oncogene revolution has shown that cancer can arise from genes alone or from interactions between our genes and what we ingest, inhale, or encounter.

D. J. Kevles

CARTOGRAPHY, the art and science of making representations of areas of the earth and other spatially extended objects, has been connected with the history of modern science both as a field of inquiry and as a tool. As a field, it has supplemented and stimulated geodesy and, later, planetary science. As a tool, it has been indispensable to geology, geophysics, oceanography, meteorology, and biology, all of which rely on thematic maps to represent and analyze spatially distributed phenomena such as magnetic variation, rock outcrops, or warm and cold fronts.

Three major events around 1500 triggered an explosion of cartographic activity in Europe. First, cartographers assimilated the lessons of Claudius Ptolemy's *Geographia*, the greatest cartographic achievement of the ancient world. Brought to Italy from Constantinople, the complete text was translated into Latin early in the fifteenth century. By the century's end, at least seven different editions had been published. From Ptolemy, cartographers learned to arrange geographical knowledge according to a coordinate system of parallels (latitudes) and meridians (longitudes) and to project the system onto flat surfaces. Second, thanks to the invention of printing and advances in engraving, cartographers found ways to reproduce maps, first as wood engravings and, in the sixteenth century, by copper engravings that made much clearer maps. Third, the voyages of discovery and increased international trade that followed produced a demand for more accurate maps of the world. Thus the chief focus of cartographers became the production of atlases.

The Low Countries were the center of atlas-making in the sixteenth century. There, Gerardus Mercator invented the famous projection that showed lines of constant direction (rhumb lines) as straight lines, just as the portolan charts of the late Middle Ages had done earlier. Mercator used this projection in the marine chart he published in 1569. In 1599, Edward Wright used the newly invented logarithms to lay out the mathematical basis of this projection. In 1570, Abraham Ortelius published one of the most comprehensive early atlases, the *Teatrum Orbis Terrarum*, with 53 maps by various authors. Numerous other atlases followed. By the eighteenth century, France had become the center of cartography. Guillaume Delisle published an atlas of 98 maps, and Jean-Baptiste Bourguignon d'Anville included 211 maps in his *Atlas général* (1737–1789).

Part of France's lead in cartography came from its research in geodesy, which led not only to a determination of the earth's shape and the length of a degree, but also to the first detailed topographical map of any nation, the *Carte géométrique de la France* (or *Carte de Cassini*). Its 182 sheets were finally completed and published by 1793, the culmination of decades of work.

Across Europe, nations founded surveys, mostly run by the military: the Ordnance Survey of Great Britain in 1791, the Institut Géographique National in France, the Landestopographie in Switzerland. The Spanish set up their topographic survey in the eighteenth century, the Austro-Hungarians, Swiss, and Americans in the nineteenth century. The Germans combined the existing state surveys into a national survey following unification in 1871. In 1888, Japan instituted its Imperial Land Survey. European nations also surveyed their overseas territories. The most ambitious of these surveys, the Great Trigonometrical Survey of India, established early in the nineteenth century, not only mapped the subcontinent but raised gravimetric problems that quickly led to the theory of isostasy.

Already in the seventeenth century, scientists had designed maps for specific scientific purposes. Between 1698 and 1700, Edmund Halley sailed the Atlantic, measured the variations in magnetic declination, and charted them on a pioneering map that appeared in different editions between 1701 and 1703. By drawing lines between points of equal variation, he pioneered the technique of isogonic lines that would be used often in later thematic maps. In the early nineteenth century, geologists invented the stratigraphic map that represented each kind of rock that outcropped at the earth's surface by a different color. Constructing such maps became the major goal of newly instituted national geological surveys. So important was stratigraphic mapping, so urgent its need for good underlying base maps, that in the United States the government gave the Geological Survey, established in 1878, the responsibility for producing the prerequisite topographic maps.

As national topographic surveys designed to promote national military and commercial interests began to publish their results, entrepreneurs founded private companies to exploit the information in maps for the use of the general public. Among the more important of the companies they founded were Bartholemew in Great Britain, Justus Perthes in Germany (an enterprise begun in the late eighteenth century), and Rand McNally in the United States.

From the 1880s to World War I, cartographers, like many other scientists, created international institutions. In 1875, the Convention of the Meter, attended by twenty nations, accepted the metric system, initially proposed in France in 1791, as the universal system of measurement. This aided the systematization of map scales. In 1884, the International Meridian Conference in Washington, D.C., decided on Greenwich, London, as the site of the prime meridian; the choice was universally accepted by World War I. At the International Geographical Congress of 1891, the German geographer Albrecht Penck proposed an International Map of the World on a scale of 1:1,000,000 in 1,500 sheets. The proposal was accepted but the work proceeded slowly. The most significant accomplishment of this still incomplete project was the 107-sheet *Map of Hispanic America* published by the American Geographical Society in 1945.

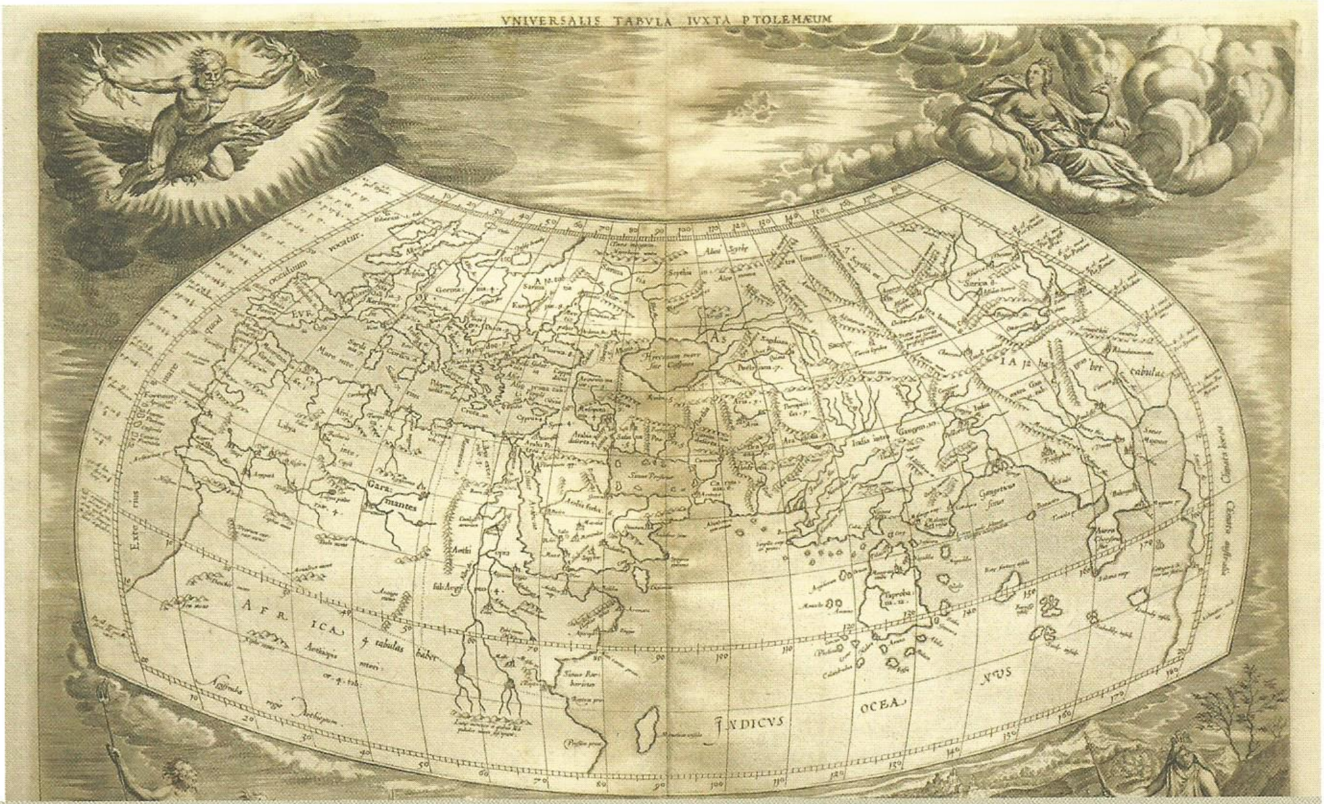
World War I brought a halt to international cooperation and ushered in the most productive century ever in cartography. In succession, the airplane, aerial photography, seismic techniques, echo sounders and sonar, radar, satellites, and computers made possible the mapping of features of the land, ocean bottoms, and extraterrestrial objects with an accuracy, ease, and variety hitherto undreamed of.

Without a growth industry in aeronautical charts, aviation would have foundered. Conversely, airplanes made aerial photography and reconnaissance mapping possible once cartographers had developed techniques to translate photographs into maps. Meteorologists responded to the needs of the aviation industry, and benefited from it as they developed theories of high- and low-pressure systems and hot and cold fronts, all of them represented on maps. Today, meteorology is a map-intensive enterprise. Seismology, the echo sounder, and sonar displaced sounding as methods of mapping underwater. The unexpected topographic features detected with these new tools helped bring about the plate-tectonic revolution.

In the 1960s, the already-important remote-sensing systems came into their own. Electronic measuring helped extend continental surveys to oceanic areas. Soon thereafter, satellite triangulation became possible, helping to tie the triangulation of the continents together into a single system. Innovations multiplied. For example, scientists developed SLAR (side-looking airborne radar) in the 1970s. After SLAR had been tested in Ecuador and Nicaragua, RADAM (Radar Amazon Commission) of Brazil and Aero Service of Philadelphia mapped the hitherto inaccessible Amazon Basin. Wide-angle cameras and improved film allowed the mapping of the earth and the moon and planets.

Computers were quickly harnessed for the purposes of mapping by institutions such as the Laboratory for Computer Graphics and Spatial Analysis at Harvard. They made the previously tedious business of laying out projections routine. After experiments in the 1970s, computers by the 1980s could translate aerial photographs into topographic maps complete with contours, allowing rapid and accurate contour mapping for the first time. Statistical mapping also became much easier.

The greatest change brought about by computers was a shift from considering the map as a completed object to the map as a manipulable tool. In the 1960s, geographers devel-



A map constructed on principles laid down by the Greek astronomer Ptolemy around 150 A.D., showing Europe, Asia, and Africa. (The Mediterranean Sea is at middle left.) Editions of Ptolemy's *Geographia* containing such maps were published before 1500.

oped computerized information systems. Instead of entering data on a two-dimensional surface, they digitalized it. This meant they could easily superimpose different sets of information and, even more important, draw conclusions based on the superimposition. With this new tool in hand, cartographers were better equipped to prepare specialized maps for business, law enforcement, natural-disaster prediction, or other specialized interests.

Today, cartography flourishes as never before. The military remains heavily involved, and the private companies multiply. Most nations have their surveys. Non-governmental groups such as the American Geographical Society and the National Geographic Society promote cartography. Professional societies such as the American Congress on Surveying and Mapping, the American Society of Photogrammetry, and the American Society of Civil Engineers (focusing here on the United States) have multiplied. They publish journals such as the *Manual of Photogrammetry, Photogrametria,* and *Surveying and Mapping.* Finally, a variety of international organizations attempt to coordinate mapping worldwide. Among them are the U.N. Office of Cartography, the Inter-American Geodetic Survey, the Pan-American Institute, and the International Hydrographic Organization in Monaco.

During most of the twentieth century, historians of cartography described how their discipline had achieved increasing scope and precision. At the end of the century, the critical cartography movement led by J. B. Harley and other British cartographers emphasized instead that, however exact maps may be, they are far from neutral. Cartographers' choice of projections, scales, symbols, and units reflect their own and their patrons' interests. According to these historians, maps depend not only on scientific knowledge but also on political interests.

RACHEL LAUDAN

CHAOS AND COMPLEXITY. Nature is complicated. Scientists trying to understand it have to simplify and approximate in order to discern regularity in phenomena and describe it mathematically. In the late twentieth century a new field called chaos theory emerged that instead embraced complexity and the nonlinear mathematical equations that expressed it.

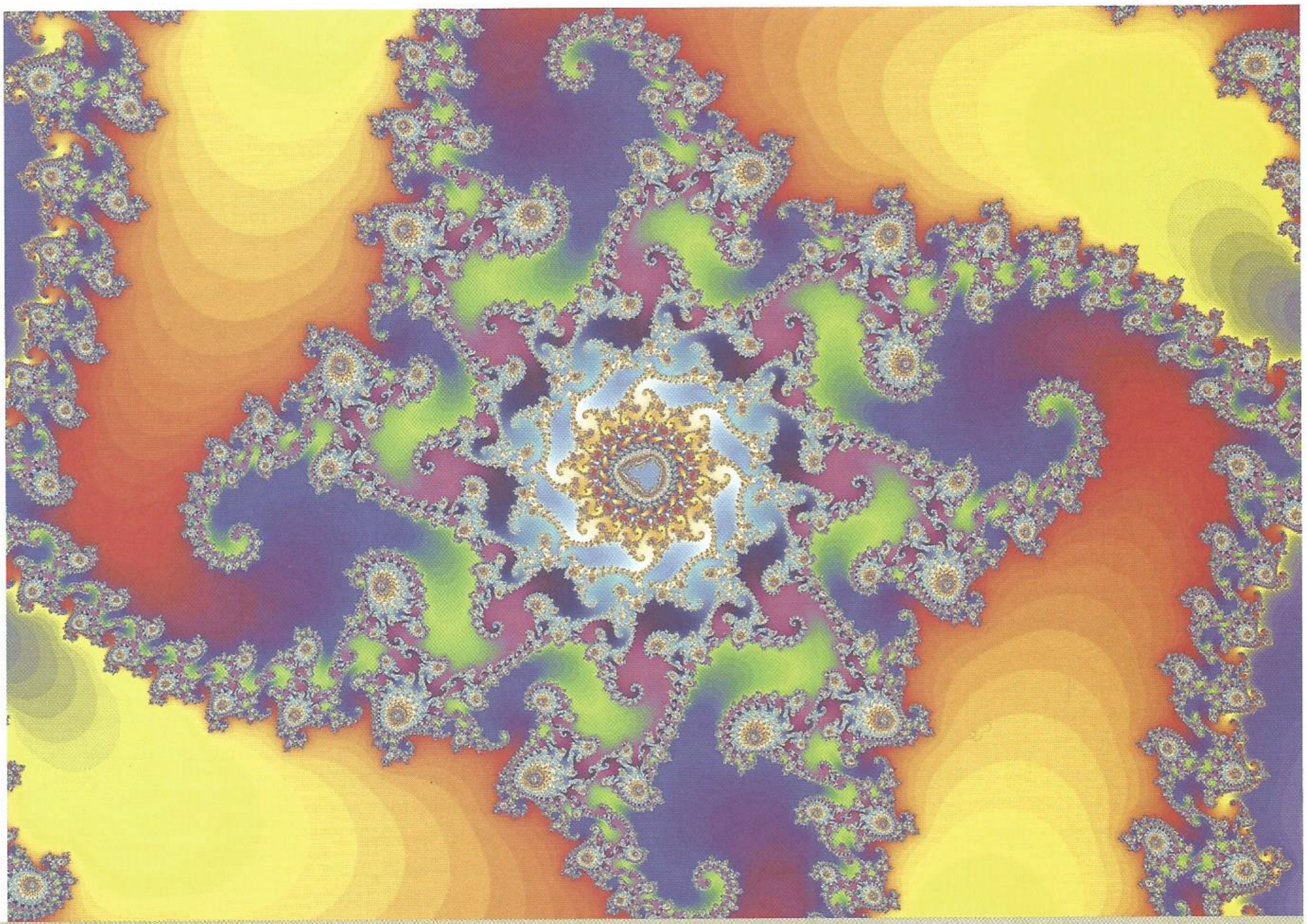
Scientists and mathematicians had previously addressed the topic of complexity and nonlinear equations, notably Henri Poincaré, who worked on the theory of differential equations and dynamical systems. In 1908 Poincaré pointed out that small differences in the initial conditions of a system could result in large changes in their long-term evolution, and noted as an example the unpredictability of the weather. But Poincaré's work did not immediately spark a new line of research; physicists at the time were fruitfully exploiting linear differential equations in the development of relativity and quantum theory.

Chaos theory first emerged from the increasing use of computers in meteorology after World War II, when computer scientists viewed the complex, nonlinear problems of meteorology as a testing ground and meteorologists used computers as a way to handle their accumulations of data and to model weather systems. In 1961 Edward Lorenz, a meteorologist at the Massachusetts Institute of Technology (MIT), was running simplified atmospheric models through his computer. He decided to retrace a run, but instead of starting at the beginning he started halfway through, typing in the numbers for the initial conditions from the printout for the first run. The printout had rounded off the six decimal places used by the computer to just three, but Lorenz assumed a difference of one part in a thousand would be inconsequential. Instead he found that the second run, from almost the same initial conditions, diverged wildly from the first. He first thought he had blown a vacuum tube, but then recognized the importance of the small difference in initial conditions.

Using a still simpler system of three nonlinear equations modeling convection, Lorenz demonstrated sensitive dependence on initial conditions, as the phenomenon was called, and cast doubt on the prospects of long-range weather forecasts. But he also revealed a sort of abstract order within the disorderly behavior that resulted: a plot of the results in three dimensions traced a complex double spiral, nonintersecting and non-repeating yet with distinctive boundaries and structure. The image, later called a Lorenz attractor, appeared with Lorenz's results in 1963, in a paper entitled "Deterministic Nonperiodic Flow" in the *Journal of the Atmospheric Sciences.* The title asserted the persistence of determinism; the avenue of publication indicated the source of Lorenz's interest in the problem and ensured that most physicists and mathematicians would miss its initial appearance.

In the meantime Stephen Smale and several other mathematicians at the University of California at Berkeley were developing ways to model dynamical systems through topology, folding and stretching plots in phase space to reproduce the unpredictable histories of nonlinear systems; two points on the plot could be close together or far apart depending on the sequence of folds, thus exhibiting sensitivity to initial conditions. In the early 1970s, mathematician James Yorke came across Lorenz's paper and publicized it in a mathematics journal, in which he applied the term "chaos" to the subject. Yorke drew on the work of Robert May, a mathematical physicist who had turned to population biology. May had found that nonlinear equations describing cyclic changes in populations could begin doubling rapidly in a period before giving way to apparently random fluctuations; but within the random behavior, stable cycles with different periods would reappear, then start doubling again toward randomness. Yorke explained May's results with chaos theory. A review article in *Nature* in May 1976 brought chaos to a still wider audience.

Yorke learned that Soviet mathematicians and physicists had been pursuing similar lines of research, starting with the work of A. N. Kolmogorov in the 1950s and extended by A. N. Sarkovskii, who arrived at the same conclusions as Yorke, and Yakov Grigorevich Sinai, who developed the theory in the framework of thermodynamics. Physicists in the Soviet Union, the United States, and Europe saw in chaos a way to tackle long-standing problems in fluid dynamics, especially regarding turbulence and phase transitions. The appearance of periodic order within longer-term disorder found visual expression in the geometry developed by Benoit Mandelbrot and other mathematicians in the 1970s. Mandelbrot coined the term "fractal" to describe the new class of irregular shapes that seemed to duplicate their irregularity when viewed at different scales and dimensions. In 1976, Mitchell Feigenbaum found that a single constant described the scaling or convergence rate—that is, the rate at which cycles doubled in period on the way to chaos—no matter the type of physical system or mathematical function (quadratic or trigonometric). Shortly after Feigenbaum announced the single universal scaling law, the first conference on chaos convened in Como, Italy. That was in 1977, fifty years after another conference of physicists there had considered the competing interpretations of quantum mechanics.



Computer-generated image derived from a Mandelbrot Set, which defines complex mappings that often resemble structures found in nature

Chaos theory emerged from diverse disciplinary and institutional origins: from Lorenz, an academic meteorologist; to Mandelbrot, working at International Business Machines (IBM) Corp. on mathematical economics; to Feigenbaum, a theoretical physicist at Los Alamos National Laboratory. Los Alamos eventually created a Center for Nonlinear Studies, and other centers for chaos theory emerged at the University of California at Santa Cruz, at Gorky in the Soviet Union, and elsewhere. Chaos theory served to bridge disparate disciplines dealing with apparent disorder: biology, ecology, economics, meteorology, and physics. Digital electronic computers were central to all of the work. Chaos also connected abstract mathematics with real-world problems. The theory provided tools for astronomers studying the red spot on Jupiter and galactic structure, population biologists modeling the fluctuations of species, epidemiologists charting the cycles of disease, physiologists investigating cardiac fibrillations, and urban engineers tracking traffic flows. A few enterprising chaos theorists sought to predict the stock market and make investors, and themselves, rich. Some practitioners viewed chaos theory as a subset of a wider field called complexity, which studied neural nets, cellular automata, spin glasses, and other exotic systems exhibiting complex interconnections among individual components.

Chaos theory emerged in the 1960s and 1970s, a time of general cultural ferment often manifested in antiscientism. Chaos theory itself seemed to reject reductionism and determinism in favor of a holistic embrace of complexity and flux, even if it still found rules and regularity buried deeper in disorder, and it thus resonated with critics of deterministic science. Several chaos pioneers themselves drew inspiration from the romanticism of Goethe. The emergence of centers for the field in Santa Cruz and Santa Fe, towns with New Age reputations, suggest the countercultural component in the chaos community.

PETER J. WESTWICK

CHEMICAL BOND AND VALENCE. In the eighteenth century and earlier, chemical combination was thought to be ruled by the laws of "chemical affinity" as measured (among other ways) by the energy and proportions in which acids and bases combine to form salts. When atomic theory and electrochemistry began to be developed almost simultaneously shortly after 1800, most theorists thought that the atoms that form chemical compounds must be held together by polar electrostatic forces. The electronegativity or electropositivity of a substance could be measured by its behavior in an electrochemical cell; the sign and intensity varied with the substance, and was a primary characteristic of each element. Developed primarily by Jacob Berzelius in the 1810s and 1820s, the theory of electrochemical dualism worked well for inorganic compounds, but by the 1830s it ran into increasing difficulties in organic chemistry.

Certain elements seemed to be able to substitute for one another in compounds irrespective of their electrochemical character. A study of inorganic and organometallic compounds led Edward Frankland in 1852 to point out that atoms of nitrogen, phosphorus, antimony, and arsenic seemed always to combine with either three or five other atoms, regardless of electrochemistry. In the late 1850s, Frankland's friend Hermann Kolbe began applying this concept to organic compounds. Even before Frankland's paper of 1852, Alexander Williamson had pointed out the "bibasic" nature of certain organic radicals, and soon he applied this concept to the oxygen atom as well. Following Williamson's lead, Charles-Adolphe Wurtz, William Odling, and August Kekulé also explored the same concept in organic chemistry, with regard to hydrogen, oxygen, sulfur, nitrogen, and ultimately carbon.

Kekulé summarized this emerging theme in two articles published in 1857–1858. He stated that atoms of each element appear to have a certain fixed capacity to combine with atoms of the same or of other elements; he called these components of combination capacity "affinity units." Hydrogen and chlorine atoms had one such unit; oxygen and sulfur two; nitrogen, phosphorus, and antimony three; and carbon four. About a decade later this concept was renamed "valence." Kekulé wrote that the formula for water, H_2O, signifies two monovalent hydrogen atoms combined with one divalent oxygen atom; ethane, H_3CCH_3, holds together because each methyl group (CH_3) has one unused valence unit of the tetravalent carbon atom, and the two valences satisfy each other in hooking together; and so on with other formulas.

This theory of atomic valence seemed to be supported by abundant evidence, and most leading chemists rapidly accepted it. Kekulé used valence concepts to develop a theory of "chemical structure." Carbon atoms, he wrote, could use some of their valences to bond together to create carbon "chains," forming the "skeleton" of a molecule. Following the valence rules, atoms of other elements, such as hydrogen, oxygen, and nitrogen, could add onto (or into) this skeleton, to form molecules of (potentially) all the organic compounds then known.

The gradual formulation of accessory assumptions, such as that of multiple bonds (ethylene as $H_2C=CH_2$, formaldehyde as $H_2C=O$, and so on), demonstrated that the structure theory could cover a wide range of organic formulas. In 1865 Kekulé showed how carbon tetravalence could be used to derive a promising candidate formula for the crucially important benzene molecule, C_6H_6, the prototype of all so-called aromatic compounds. This formula suggested a closed ring of six carbon atoms with alternating single and double bonds, and with a hydrogen atom attached to each carbon. Chemists soon accepted Kekulé's benzene theory.

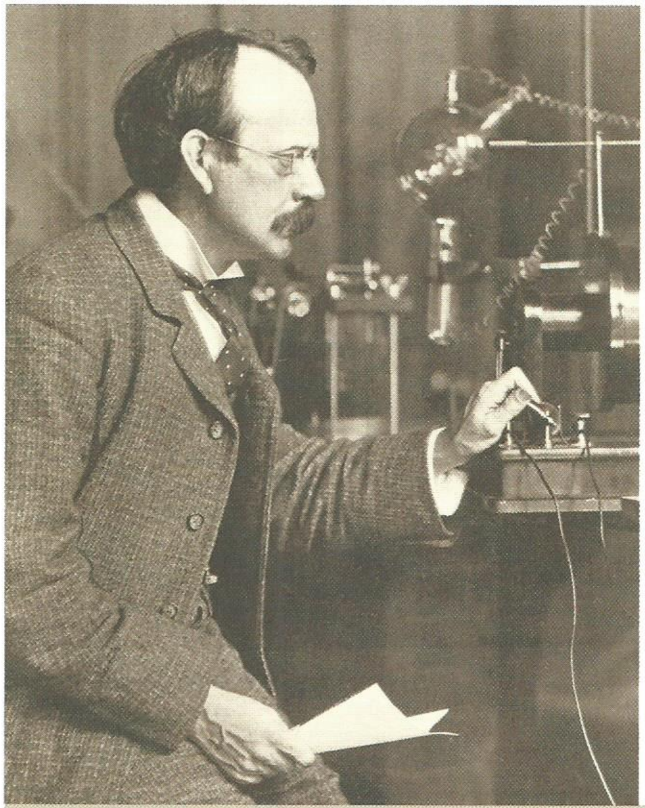
Despite their important roles in its initial formulation, Frankland and Kolbe rejected the full implications of valence and structure theory, though Frankland's resistance collapsed quickly in the early 1860s. One problem they identified was the number of additional assumptions necessary to make the theory work well. Moreover, it was not clear whether valence was a constant property, characteristic of each element, or variable with chemical circumstances, as Frankland had initially proposed. Disputes about the fixity of valence continued for decades.

Some chemists objected that the valence connections between atoms resembled crude "hooks" or "glue" rather than an isotropic (spatially uniform) natural force such as gravitational or electrical attraction. Frankland referred to valence connections as chemical "bonds," but demurred at describing them further. Gravitation seemed to be excluded as the cause of valence owing to the complexity and stability of chemical compounds; electrical attraction seemed impossible because atoms of a single element could bond to each other. Therefore, accepting the idea of valence appeared to require renouncing the possibility of understanding chemical affinity as a familiar macroscopic physical force. It was a new and uniquely chemical concept.

The residual anomalies associated with Kekulé's highly successful benzene theory led to new proposals by Lothar Meyer, Henry Edward Armstrong, and F. K. Johannes Thiele that invoked partial or center-directed valence bonds. In 1874, J. H. van't Hoff and Joseph Le Bel began to explore valence bonds in three dimensions. In the 1890s, Alfred Werner used a modified valence theory successfully to represent the molecular composition of certain complex inorganic substances ("coordination compounds"). In this endeavor he made use of the recently formulated theory of ionization of Svante Arrhenius.

When J. J. Thomson demonstrated the existence of the electron (1897), some physicists and chemists immediately began to inquire whether this offered a new way to understand valence. In 1904, Thomson developed an atomic model in which electrons were supposed to circulate in exterior shells. In the same year in Berlin, Richard Abegg formulated a more explicit "rule of eight," corresponding to periodic valence regularities.

During and just after World War I, Walther Kossel and Gilbert N. Lewis began independently to develop electronic theories of the chemical bond, a concept fruitfully extended shortly thereafter by Irving Langmuir. Neutral atoms have as many electrons outside the nucleus as protons within. In the new theory, the second and third periods of the periodic table each have eight members, the last of which has a stable nonbonding "octet" of electrons in a shell. Beyond the octet shells are the odd electrons in the outer shell, the "valence electrons," which can be shared with adjacent atoms to form chemical bonds. For instance, aluminum, with atomic number 13, is eleven places past helium in the periodic table, or three places past the first stable octet. The aluminum atom therefore has three valence electrons available to share with other atoms—a valence of three.



Joseph John Thomson, discoverer of the electron and director of the Cavendish Laboratory, Cambridge, England, at work in 1904

La calcination Solaire de Lantimoine.
a
b
c
d
e
a laTable
b le miroir auec son soution
qui se peut hausser et baisser
c la pierre ou la plaque sur lag
est l'antimoine en poudre.
d l'artiste qui gouuerne le
miroir et qui remue lantimoin
e la lumiere qui est concentre
par le miroir.

Some early photo-chemistry: the chemist is focusing the sun's rays so as to oxidize a piece of antimony.

Langmuir thus distinguished an "ionic" bond, where an electron transferred from an electropositive to an electronegative atom, from what he called a "covalent" bond, where the two electrons, one from each atom forming the bond, were shared more or less equally. In the first case, coulombic attraction held the atoms together; in the second case, electricity was involved in a manner not understood until the advent of quantum mechanics.

Neils Bohr and his collaborators began to develop their theories of electronic structure by examining atomic spectra with reference to quantum principles and the basic patterns revealed by the periodic table. Meanwhile, work on wave mechanics by Louis de Broglie and Erwin Schrödinger began to provide theoretical explanations for the spatially directed nature of valence bonds. In the late 1920s and early 1930s, Walter Heitler, Fritz London, John Slater, Linus Pauling, and others developed "valence-bond theory" as an application of the new quantum mechanics of Erwin Schrödinger and Werner Heisenberg. This involved constructing wave functions to represent the older Lewis-style electron pairs of a covalent bond.

At about the same time, Robert Mullikan developed an alternative quantum-mechanical technique for understanding chemical bonding based on what he called "molecular orbitals." Erich Hückel applied both valence-bond and molecular-orbital methods to the problem of aromatic compounds and found Mullikan's method superior. The molecular-orbital approach seemed to many to provide a cleaner and more satisfying model, and after World War II it gradually displaced the valence-bond model championed by Pauling.

Both valence-bond and molecular-orbital approaches had led to the idea of "resonance": the bonds between the carbon atoms of the benzene ring could not be considered either as single or as double bonds, but rather as uniform "resonance hybrids" halfway between the two states. Theories of resonance have successfully accounted for the curiously passive character of aromatic compounds toward addition to the double bonds of the ring, and the concept of "aromaticity" has broadened to include nonbenzenoid compounds.

After welcoming and then abandoning electrical theories of chemical bonding in the course of the nineteenth century, chemists in the twentieth century, armed with physical theories of the atom and quantum-mechanical principles, embraced them once more, and with considerable success. Chemists still have a long way to go, however, in developing theoretical models for the observed chemical behavior of molecules.

A. J. ROCKE

CHEMISTRY. The term chemistry first appeared in references to a practice consolidated in Alexandria at the beginning of the Christian era, and known later as the "Egyptian" art. Historians of chemistry have characteristically distinguished chemistry from alchemy, a product of the Arabic and European Middle Ages and later depicted as a secrecy-laden search for methods to produce noble metals by transmutation and to obtain the mysterious philosophers' stone. According to this story, chemistry emerged during the late sixteenth and seventeenth centuries. Drawing on practices of alchemy, metallurgy, and herbalist distillers, chemistry distinguished itself from its earlier roots both by its openness and its goal: the determination of the composition of substances drawn from the plant, animal, and mineral kingdoms by separating them into their elementary constituents. Recent historians, however, believe that until well into the seventeenth century alchemy and chemistry were synonymous terms that denoted a broad range of inquiries, and that only after practitioners of chemistry wished to distance themselves from the seekers of gold and the philosophers' stone did they narrow the definition of alchemy to activities they discountenanced.

The remarkable stability of the identity of chemistry despite deep mutations in its aims and conceptual frameworks rests on the nature of the place in which it has been practiced, from the earliest times of which we have records to the present. The original meaning of "laboratory" was the space in which chemists "elaborated" chemical and medicinal substances. Chemists traditionally assembled in their laboratories a characteristic set of apparatus capable of a well-defined repertoire of operations. With furnaces and distillation apparatus constructed from components made of earth, metal, or glass, they attempted through the agency of fire to separate substances into their volatile and fixed components. Filtration, solution, precipitation, maceration, solvent extraction, and other operations were usually subsidiary to the central procedures of distillation and sublimation.

During the seventeenth century, a series of textbooks, of which the prototype was Andreas Libavius's *Alchemie* (1597), organized knowledge of chemical substances and operations into teachable form. They culminated in the popular *Cours de Chymie* of Nicolas Lemery, first published in 1673. He and other chemists in France gave chemical lectures and demonstrations at the Jardin des plantes and in their apothecary shops. In the German principalities, chemical instruction entered the universities during the seventeenth century, an early example being the teaching of chemical medicine at the University of Marburg (1609). By the end of the century, chemistry had become a sufficiently distinct branch of natural knowledge to form, together with physics, anatomy, and botany, the physical section of the French Academy of Sciences. In England, Robert Boyle led those who sought to make chemistry part of the broadly forming new natural philosophy.

Seventeenth-century chemists interpreted their separations by theories of matter through hybrids drawn in part from the three "principles" (salt, sulfur, and mercury) adapted by Paracelsus from alchemical views, and in part from the four-element theory of Aristotle. The most common compromise identified the products of a distillation as oils (characterized by the combustible principle, sulfur); "spirituous" liquids (mercury); insipid liquids (water); substances soluble in water (salt); and fixed insoluble substances (earth). At a more pragmatic level, there gradually emerged a scheme in which metals, alkalis, and "absorbent earths" could be separated from and recombined with the three known mineral acids and a "vegetable" acid. Boyle's systematic application of color indicators able to detect the presence of acids and alkalis facilitated these identifications.

The incorporation of the mechanical philosophy into chemistry during the second half of the seventeenth century abetted the interpretation of chemical processes as consequences of the particular shapes of the ultimate participating particles. Sharp-pointed acid particles embedded themselves in pores in alkali particles, resulting in a salt that displayed neither the properties of the acid nor the alkali, but from which both could later be recovered.

During the first half of the eighteenth century, chemists gradually subordinated early theories of matter to the more pragmatic concept of neutral salts formed of an acid and a base. Elaborate mechanistic explanations gave place to the more generic particulate picture. In 1718, Etienne-François Geoffroy systemized the well-defined chemical changes then known in a Table of Rapports, the columns of which indicated the order in which substances would replace one another in combination with the substance shown at the top of each column. During the following decades, chemists adopted Newton's idea that differential short-range forces of attraction, or "affinities," drove these replacements.

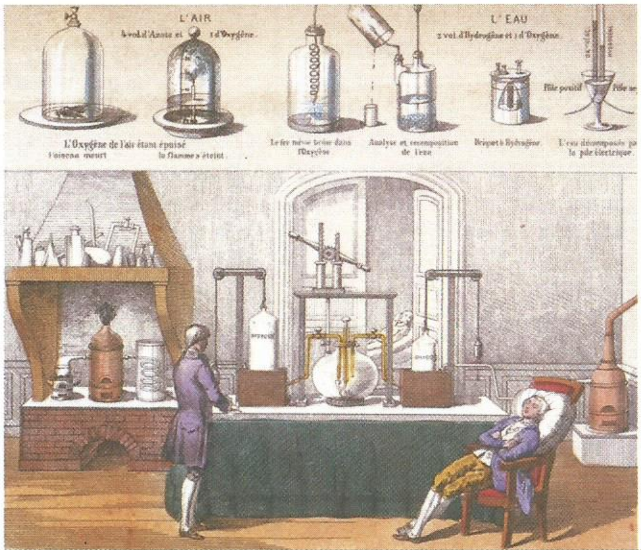
Chemists continued to support their activities largely from apothecary shops. The teaching of chemistry in German medical faculties expanded. A group of chemists in the reformed Paris Academy of Sciences became a leading forum for the pursuit of experimental chemistry in the first three decades of the eighteenth century. At the Prussian Academy of Sciences, reformed by Frederick II, Andreas Marggraf and Johann Pott became prominent after 1750 in the investigative expansion of the chemistry of salts and in their application to both plant and mineral analysis. The growing sense of a chemical community in Germany gave rise in 1778 to the first specialized chemical periodical, *Chemisches Journal*, edited by Lorenz Crell.

Because fire figured so prominently in their operations and distinctions, chemists were much concerned to explain combustion. Chemists long associated combustibility with the sulfur principle because common sulfur conspicuously burned. The dominant form of this approach in the eighteenth century was Georg Ernst Stahl's theory of phlogiston. Stahl recognized that the calcination of metals and the reduction of metallic ores to their metallic form, as well as the relationship between sulfur and vitriolic acid, could all be explained as exchanges of the same principle. Phlogiston served to link an extensive series of the most important chemical changes known at the time into a coherent system.

Until the late eighteenth century, chemists operated mainly on solids and liquids. Since vapors could not be handled by ordinary techniques, they were usually neglected in accounting for the substances that entered or left during a chemical change. Atmospheric air was regarded as an elementary, homogeneous, elastic fluid, which could contain various impurities. In 1756, following up earlier work by Stephen Hales, Joseph Black showed through quantitative balance experiments that ordinary alkalis contain a distinct species of air, which he named "fixed air." During the next two decades, several British natural philosophers discovered other "airs." In 1775, the most prolific of these discoverers, Joseph Priestley, discovered (by reducing mercury without charcoal), a "purer and more respirable" air than the atmosphere. Extending the phlogiston theory to explain the properties of the various new airs, Priestley named his discovery "dephlogisticated air."

In 1772, Antoine Laurent Lavoisier took up the problem of the absorption and release of air. His discoveries that phosphorus and sulfur gain weight when burned, and metallic calces lose weight when reduced, led him to a distinctive quantitative style of experiment, the so-called "balance-sheet method," which many historians identify as the basis of the modern science of chemistry. In 1777, Lavoisier proposed a new general theory of combustion, dispensing with phlogiston, in which "pure" air combined with metals and combustible bodies, releasing the material principle of heat. Soon he renamed this principle "caloric" and pure air "oxygen," which, as its Greek root implies, is regarded as the principle of acidity.

By 1785, Lavoisier's demonstration of the decomposition and synthesis of water consolidated his theoretical structure and converted several influential French chemists to his side. They lobbied chemists who visited Paris, founded a new journal, and collaborated to reform chemical nomenclature. Although Priestley never acceded to the "French chemistry," other British chemists, as well as the Germans who remained loyal to the Stahlian viewpoint until 1790, rapidly adopted the essential features of Lavoisier's reform during the last decade of the century.



An engraving from 1860 depicting pneumatic experiments done with the apparatus of the late 18th century

To help consolidate what supporters and opponents alike were calling a revolution in chemistry, Lavoisier published a *Traité élémentaire de chimie* (1789) that summarized the experiments and theories on which he had based his movement, incorporated into the new framework earlier knowledge of the chemistry of salts, and presented recent applications of the new theory of combustion to organic substances. In addition, the *Traité* replaced the traditional chemical elements, which Lavoisier regarded as "metaphysical," with a pragmatic definition of elements as substances that "we have not been able to decompose by any method." His list of elements provided the basis from which the modern periodic table of elements has grown.

In principle, eighteenth-century chemists recognized a hierarchy of levels of composition, from elements to various orders of "mixtes," but the only levels generally established through analysis and synthesis were salts and their constituent acids, metals, alkalis, and alkaline earths. Chemists often assumed that these constituents were present in fixed proportions because a specific quantity of an acid was required to neutralize a particular quantity of a base. At the end of the century, Claude-Louis Berthollet challenged this assumption. From the principle that substances combine because of general laws of attraction, Berthollet inferred that compounds could form in an indefinite series of proportions, depending on the relative masses of the constituents placed together. Joseph Proust argued that true compounds occurred only in fixed proportions. Their debate ended indecisively, but contributed to a clearer distinction between chemical compounds and solutions, mixtures, or alloys.

Along with his attack on fixed proportions, Berthollet broke with eighteenth-century affinity theory, according to which a substance with greater affinity for one of two substances combined together will completely displace the substance of lesser affinity. Instead, according to Berthollet, an equilibrium sets in that depends on the relative masses of each of the substances present. His idea took hold gradually, culminating in the 1860s to quantitative laws of mass action.

Considerations about the composition of the atmosphere led John Dalton during the first years of the nineteenth century to identify chemical atoms with characteristic atomic weights. By assuming that when only one compound of any two elements was known it consisted of one atom of each, that when two were known one of them consisted of one atom of each, the second of two of one and one of the other, and so on, Dalton calculated, from the measured proportions by weight of the elements, the relative weights of their atoms. In 1808, he published atomic weights for thirty-six elements relative to hydrogen = 1. Dalton conceived of his atoms as hard, spherical bodies, and depicted their assumed spatial arrangements in the compounds they formed.

Several prominent English chemists, including Thomas Thomson and William Hyde Wollaston, adopted Dalton's atomic theory after obtaining independent evidence for multiple combining proportions. To avoid commitment to the reality of the atoms, Wollaston referred to "equivalent" rather than atomic weights, but he calculated them in Dalton's manner. In Sweden, Jöns Jacob Berzelius accepted the general principle of the atomic theory, but established more rigorous standards of experimental precision for determining atomic weights. Those that he established during the first two decades of the century were generally accurate to within 1 percent. In place of Dalton's "law of simplicity," Berzelius devised rules and analogies by which to decide on the empirical formula for a given compound. Since chemists operated with several sets of rules, they produced atomic weights for some elements that differed by small integral multiples.

The invention of the battery (pile) by Alessandro Volta in 1800 influenced chemistry powerfully. Anthony Carlisle and William Nicholson found even before Volta's paper was published that the current generated by the pile can decompose water into its elements. During the next decade, Humphry Davy passed a current through alkaline solutions to isolate the metals potassium and sodium. Later he recovered magnesium, strontium, calcium, and barium from amalgams of the alkaline earths. Because the electric current could overcome the force of the affinities supposed to hold substances together in compounds, Davy inferred that affinities were electric forces. Berzelius, who also experimented extensively with Voltaic currents, developed a general theory of chemical composition based on the same assumption. According to Berzelius's "dualistic theory," oxides formed between highly negative oxygen and positive, or less negative, atoms. The remaining net positive or negative charges of these oxides allowed them to combine into neutral salts and other more complex compounds.

The discovery in 1810 by Joseph Louis Gay-Lussac that gases combine in ratios of small whole numbers by volume provided a potential resolution of uncertainties over atomic weights. One needed only the additional assumption that a given volume of any gas contains the same number of atoms (or molecules). Some, including most famously Amedeo Avogadro and André Marie Ampère, devised theories based on this conclusion, but Dalton rejected the generalization that all gases contained the same number of particles in the same volume. The consequence that individual molecules of several elementary gases must then be composed of multiple identical atoms caused other prominent chemists to reject or restrict the generalization.

By the second decade of the nineteenth century, chemists had established fundamental principles sufficient to support rapidly growing investigative and educational activities. New institutional arrangements strengthened the role of chemistry in higher education. In France, the École Polytechnique, set up during the Revolution, included lectures and laboratories in chemistry. Leading chemists, such as Gay-Lussac and Louis Jacques Thenard, became professors there, at the Collège de France, or at the University of Paris, and gave lectures that attracted large audiences. Aspiring foreign chemists came to Paris to learn from these masters of rigorously logical exposition and experimental demonstration. In London, Davy achieved great popularity through his chemical lectures at the Royal Institution. Chemical instruction took place in Germany in several universities, and especially in small proprietary pharmacy schools. One of those who began his education in Germany, but continued it in Paris, was Justus Liebig. After working with Gay-Lussac, Liebig returned to his native state of Hesse in 1824 with an appointment to teach chemistry at the small University of Giessen. There he developed a teaching laboratory, intended at first to train pharmacists toward instruction in general chemistry. By the mid 1830s, Liebig's laboratory was training dozens of chemists and pharmacists in a systematic program that moved from elementary exercises to original research projects.

The laboratories in which these activities took place resembled earlier ones but now were also centers for innovations in apparatus and procedures. Lavoisier had initiated the break from the traditional array of material objects that had long characterized the places where chemists worked.

Sometimes adapting and combining customary retorts and pneumatic troughs, sometimes designing, for particular purposes, apparatus that was quite unfamiliar, Lavoisier increased both the range and the cost of chemical equipment dramatically. Some of his designs, such as the Baroque gazometer depicted in his *Traité,* his successors simplified. But by the 1820s, chemists so regularly designed and redesigned apparatus for more special operations and for better precision that publications began to appear to keep them informed of the latest developments in laboratory organization and equipment.

As modern chemistry emerged in the nineteenth century, the traditional small-scale commercial producers of various chemicals grew into a heavy chemical industry. By the 1830s, factories rather than shops produced sulfuric acid and soda. Historians often treat this early stage of industrialization as independent of the Scientific Revolution. Chemical crafts and deliberate chemical experimentation with the intention to advance the science were closely interwoven by the early eighteenth century. What each owed to the other differed from case to case.

By the mid-nineteenth century, chemists comprised the most prominent class of the new genre of scientists. With roots in long-established practices, driven forward first by the chemical revolution identified with Lavoisier, and then by the atomic theory associated with Dalton, chemists led the way into what fin-de-siècle spokesmen called the "century of science." The laboratories that had been their peculiar abodes for several centuries now became the prototypes for the places in which other fields, such as physiology, began to establish themselves. Whatever may have been the source of the earlier development of industrial chemistry, chemists were confident that further advances depended on the application of chemical science to factory production. By the 1840s, Justus Liebig could proclaim in his *Familiar Letters on Chemistry* that the wealth of a nation could be measured by its chemical production.

No sooner had chemistry crystallized as a modern scientific discipline than it began to split into subfields. First, organic chemistry separated from inorganic chemistry. Lavoisier had already applied his theories and methods of combustion analysis to determine the elementary composition of plant and animal matters. A generation later, several leading chemists took up the problem of obtaining the quantitative precision that had eluded him. By the 1820s, they had shown that organic compounds conformed to the laws of combining proportions. The application of principles of composition derived from the study of inorganic compounds ran into severe difficulties. The discovery of compounds identical in elementary composition, but different in properties, showed that empirical formulas did not fully characterize them, and set off decades of controversy. A series of "radical" theories proposed during the 1830s posited groups of elements that remained constantly associated while taking part in the reactions that transformed the organic compounds of which they formed constituent parts. The substitution theory asserted, on the other hand, that one element within a radical or compound could be exchanged for another, such as chlorine for hydrogen, without deeply altering the properties of the molecule.

Meanwhile, as the focus in organic chemistry shifted from the analysis of substances derived from plants or animals to the derivation of carbon compounds from them by partial decomposition, substitution, and later by synthesis, another field, most often called physiological chemistry, arose to take up the problems lost in the shift. By the early twentieth century, physiological chemistry had evolved into biochemistry. Liebig's efforts, beginning in 1840 to apply the new chemical knowledge to improve agriculture, had already become a focal point for the formation of agricultural chemistry.

Around 1850, organic chemists still used competing theories of composition, different systems of atomic weights, and several versions of the letter symbols that Berzelius had introduced to represent atoms. In addition to using empirical formulas, chemists used various "rational" formulas that grouped the atoms within a molecule into several "types." Generally they regarded these types not as literal descriptions of the spatial arrangement of the atoms, but as means to classify organic compounds, to understand their relationships to one another and their reactions. From these efforts emerged generalizations about the proportions in which elements and radicals combined with one another that gradually produced theories of chemical combination applicable to both organic and inorganic compounds. Put in their most general form by August Kekulé beginning in 1857, these new views underwrote the classical theory of valence and the basis for structural formulas of organic compounds. Organic chemistry enjoyed a rapid expansion, remaining the dominant subfield of chemistry for the rest of the century.

Debates over the constitution of organic compounds during the 1850s ended in reforms of the system of atomic weights that achieved consistent interpretations of the relations between compounds. Among the most influential proposals were those of Charles Gerhardt, based in part on the views of Auguste Laurent. These efforts culminated at the first international Congress of chemists, which met in Karlsruhe in 1860 to standardize atomic weights and chemical notation. There, Stanislaus Cannizzaro circulated a proposal that although not immediately accepted, afterward quickly resolved the outstanding differences.

From the time it first coalesced during the seventeenth century, chemistry shared a wide borderland with other branches of physical science. Its theories of matter borrowed from Aristotelian natural philosophy and then from the mechanical philosophy. Even within their own operational domain, chemists of the eighteenth century distinguished between the "physical" and the "chemical" properties of the substances they studied. At the end of the eighteenth century, the exploration of the properties of heat and of gases again blurred the boundaries between chemistry and what was by then emerging as a discipline of experimental physics. The rapid growth of chemical investigations oriented around accurate combining proportions, the atomic theory, and the isolation and analysis of organic compounds seemed to distance chemistry from a physics defined around a different set of problems and methods. Nevertheless, the investigation of electricity and other phenomena common to both fields often pierced the boundaries. During the second half of the nineteenth century, a new subfield arose, deliberately situated at this persistent interface.

The discipline of physical chemistry was formed by Jacobus Henricus van't Hoff, Svante Arrhenius, and Wilhelm Ostwald. They concentrated on the application of thermodynamics to chemical processes the causes of chemical affinity, and the properties of solutions. The central importance of Arrhenius's theory of ionization to the new field earned them and their followers the sobriquet "ionists." Begun in Germany, the field spread most rapidly after 1900 in the United States under the leadership of a generation trained in the laboratories of Ostwald and Van't Hoff.

Until nearly the end of the nineteenth century, the atom as conceived and employed by chemists and physicists had little in common. The physical atom, usually called "molecule," was defined mainly by the kinetic theory of gases, while chemical atom functioned as a unit of composition defined by its atomic weight. The situation changed after physicists identified the electron and the nucleus as the principal subunits of the atom. During the first decades of the twentieth century, several chemists proposed theories of chemical affinity and valence based on the view that electrons in the outer shells of atoms form chemical bonds. The most influential of these theories, published by Gilbert N. Lewis in 1916, connected the electronic structure of the atom with the properties of the elements defined by their place in the periodic table. Reviving in a new form the electrochemical theory of Berzelius, Lewis postulated that covalent bonds consist of an electron pair shared by two atoms, whereas an ionic bond results from the transfer of an electron from one atom to another atom to form a pair that holds the molecule together electrostatically.

The development of physical chemistry and the elucidation of the electronic structure of the atom gave rise to a school of chemists who sought to describe the reaction mechanisms of organic compounds in terms of the positive and negative regions of molecules, the displacements of electrons, and the formation of transient intermediate compounds. Systematized by Christopher Ingold during the 1930s, these efforts culminated in the formation of the subfield of physical organic chemistry.

Meanwhile, quantum mechanics declared that the properties of the chemical elements and their combinations could be explained by the basic laws of physics. It referred the chemical bond to the distribution of the electrons believed to form both ionic and covalent bonds. In the event, however, the quantum mechanical equation could not be solved for complex molecules. Chemists and physicists had recourse to approximate solutions, combined with other knowledge of the properties of compounds and the nature of their reactions. The leading figure in this development was Linus Pauling.

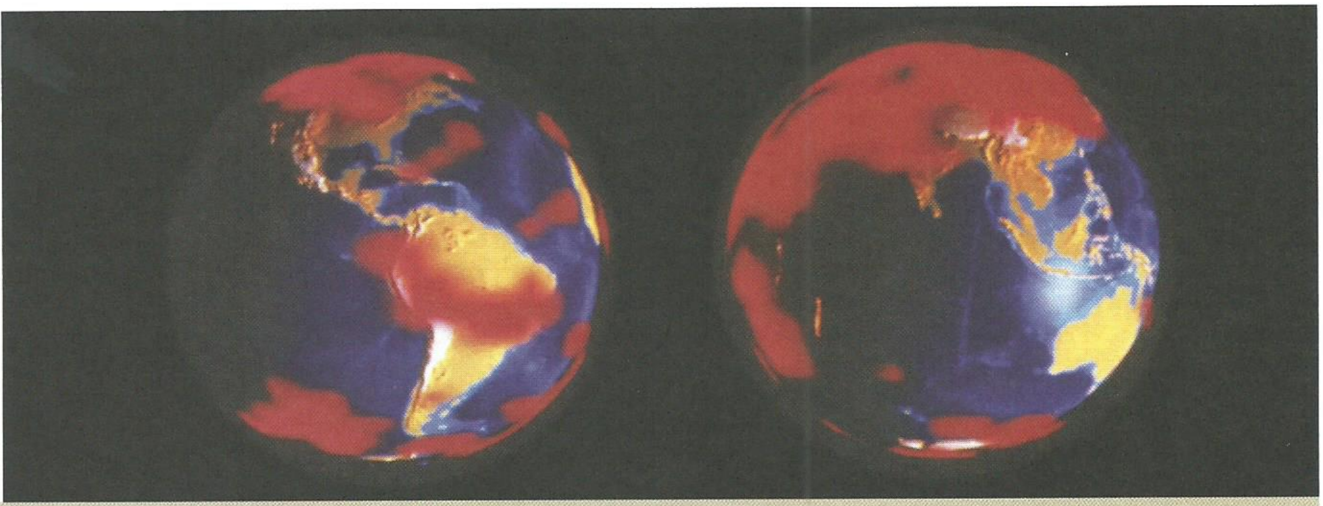
Chemical laboratories and chemical industries continued to grow in size and complexity during the second half of the nineteenth century. The synthetic dye industry became possible through the growing capabilities of chemists both to synthesize naturally occurring organic compounds and to produce previously unknown compounds by modification of the natural ones. German industry led the way in this development. At first drawing on the knowledge of academic chemists, these industries soon began to hire chemists to work directly on the discovery of new dyes, creating the first industrial research laboratories. The special problems and expertise required to scale up laboratory operations for volume production gave rise to the profession of chemical engineering.

During the early twentieth century, new classes of chemical industry emerged. The increasing worldwide demand for fertilizer led to the invention of catalytic processes requiring very high temperatures and pressures to obtain nitrogen from the atmosphere. The best known of these was the Haber-Bosch process for ammonia synthesis. World War I deprived France, Great Britain, and the United States of the supplies of chemicals previously acquired from Germany and stimulated the growth of chemical industries that afterward became strong competitors with Germany. World War I also saw a great expansion of chemical plants devoted to munitions and poison gas.

After World War II, the traditional character of the chemical laboratory began to change. Physical instrumentation became more prominent, and automated analytical methods replaced some of the chemist's traditional skills. To some observers, chemistry lost its status as a fundamental science. Quantum chemistry appeared to be merely an application of physics to the particular phenomena that chemists studied. As the applications of chemistry to many other fields of science and technology multiplied, concern whether it retained any core unity intensified. It had come to be, in the words of one general history of the subject, a "field without a territory," existing both "everywhere and nowhere." Others have argued, however, that even though its most fundamental principles may be borrowed from physics, extension of these principles to the wide range of chemical phenomena still requires methods of reasoning and investigation that have long been characteristic of chemistry.

Frederic Lawrence Holmes

CLIMATE CHANGE AND GLOBAL WARMING. Theories of climate change date from very early times; Theophrastus (371–287 B.C.) wrote on desiccation wrought by deforestation. His work, revived in the Renaissance, helped fuel concern over deforestation in European colonies, and



Computer-generated models of the earth showing the effects of global warming after twelve years during which the CO_2 content of the atmosphere is twice that at present. Red marks regions where the surface temperature has risen by more than 5°C.

In 1996, British embryologist Ian Wilmut (born 1944) created "Dolly," the world's first sheep cloned from an adult sheep cell.

from the late eighteenth century onward, colonial governments established forest reserves that were among the earliest measures of environmental conservation. Meanwhile, Enlightenment students of the classical world uncovered literary evidence for climate change since ancient times, while Americans such as Thomas Jefferson argued that deforestation from European settlement had moderated the climate, rendering it fit for civilization. Nineteenth-century climatologists, applying more exacting historical and scientific analysis to these questions, found no convincing evidence of climate change in historical times.

Climate change on astronomical and geological timescales on the other hand was more nearly certain. From Buffon, Kant, and Laplace to Lord Kelvin and beyond, cosmologists speculated about the long-term cooling of the earth from its origin as a molten ball and about the longer-term cooling of the sun. Nineteenth-century geologists found indisputable evidence in fossils of a warmer climate in ancient times, and around the middle of the century, discovered the ice ages. In order to reconcile these discoveries with his belief in a uniform state of the earth, Charles Lyell developed a theory of cyclical climate change, according to which "all... changes are to happen in future again, and iguanodons...must as surely live in the latitude of Cuckfield as they have done so."

Several eighteenth- and early nineteenth-century natural philosophers and mathematicians, including Horace Bénédict de Saussure, Joseph Fourier, and Claude Pouillet, had noted the atmosphere's selective transmission of heat; Fourier compared the atmosphere to the glass of a greenhouse. Beginning in 1859, John Tyndall began experiments on the radiative properties of atmospheric gases, and speculated that variations in their amounts might have altered the earth's climate on the geological time scale. In 1895, Svante Arrhenius, trying to explain the Ice Ages, calculated temperature changes from variations in carbon dioxide. Two decades later, he predicted that industrial generation of CO_2 would protect the globe from recurring ice ages and allow increased food production for a larger world population. Arrhenius's ideas were welcomed by the American geologist T. C. Chamberlin, who, in the first three decades of the twentieth century, developed a theory of the atmosphere as a large-scale geological agent based on a carbon cycle. Crustal uplifts expose large surface areas to weathering, a process that absorbs CO_2; global cooling and glaciation follow. The cycle turns about when mountain ranges reduce to nearly base levels.

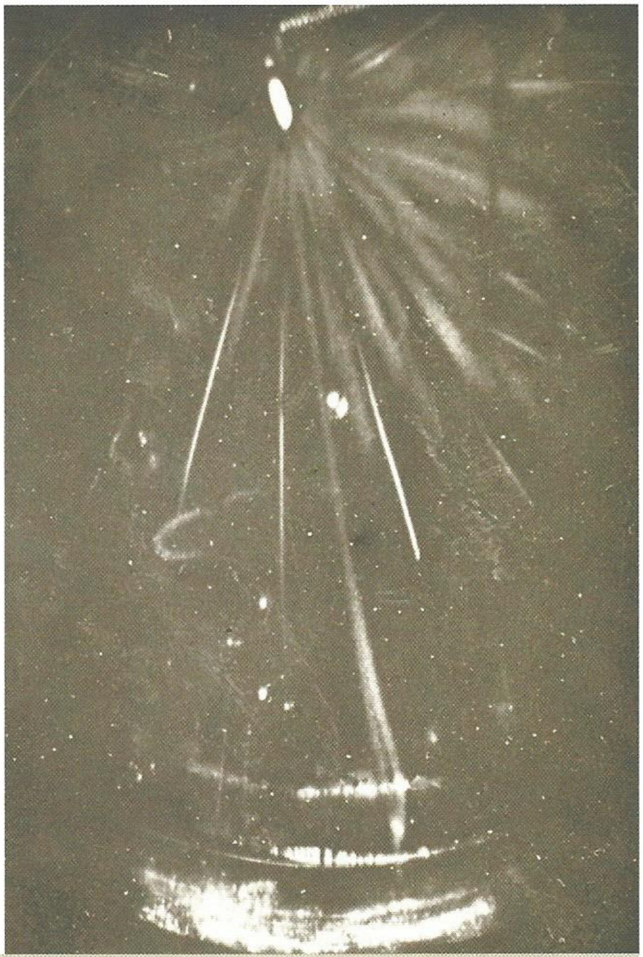
By the 1950s, alteration in insolation—solar radiation received by the earth—orbital changes, mountain building, and volcanism had all been identified as agents of climate change. Water vapor eclipsed CO_2 as an agent of global warming until G. S. Callendar published a series of articles from 1938 to 1961 emphasizing anthropogenic influences on the amount of carbon dioxide in the atmosphere. Political tension feeds fears of climate degradation, and the Cold War intensified anxiety over both global cooling and global warming. Proposals were floated for large-scale interventions such as damming the Bering Strait, orbiting fleets of mirrors in space, and spraying sulfur dioxide into the upper atmosphere. Today, the scientific community has reached a consensus that CO_2 levels have increased owing to industrial activity and that warming is taking place on a global scale. The relation between these two phenomena remains in doubt, as well as the role of other factors and the future course of climate change.

THEODORE S. FELDMAN

CLONE. Clones, genetically identical copies of living organisms, were first produced with certain plants by the cultivation of a stem or branch of the original. The process originated in ancient times and is widely used by horticulturalists and home gardeners to obtain reproductions of fruit trees, vines, and roses. The biologist J. B. S. Haldane took the word "clone," which he coined in 1963, from the Greek word for "twig." Scientists applied the term to the replication of genes themselves beginning in the 1970s, when the new techniques of recombinant DNA permitted them to snip out individual genes from an organism's genome and insert them into bacteria, where they would multiply with the bugs. The chemist Kary B. Mullis's invention of the polymerase chain reaction (PCR) in 1983 enabled scientists to produce a billion clones of a gene in a test tube.

In the late 1920s, the German embryologist Hans Spemann had achieved a type of animal cloning by inserting the nucleus from a salamander embryo cell into a denucleated egg that then developed into an independent salamander. In 1938, by then a Nobel laureate, Spemann proposed that it might be possible similarly to clone an adult animal. But he described the experiment as "fantastical," partly because he did not know how to do it, partly because he did not know whether the nucleus from an adult animal's fully differentiated cells possessed the capacity to direct the full development of the organism from the egg.

In 1951, Americans Robert Briggs and Thomas J. King, biologists at the National Institutes of Health, cloned embryonic frog cells but failed in attempts to clone more differentiated ones. Their results, along with those from other laboratories, indicated that the older the cells from which the nuclei came, the less likely the clones would develop. In 1962, John Gurdon, a developmental biologist at Oxford University, reported that he had been able to produce fully developed frogs by cloning putatively differentiated cells from the intestinal linings of tadpoles. Gurdon argued that his experiment, although successful only 2 percent of the time, confirmed that fully differentiated cells retained the genetic capacity to direct development. Other embryologists could not replicate his results. Biologists working on farm animals were able to clone horses, pigs, rabbits, and goats from early embryo cells, but most considered cloning from adult cells impossible.



One of the first photographs of tracks of subatomic particles in a cloud chamber. Alpha particles from radium made the tracks; the chamber's inventor, C. T. R. Wilson (1869–1959), made the picture at the Cavendish Laboratory, Cambridge in 1911.

In the mid-1990s, however, Ian Wilmut, a biologist at the Roslin Research Institute in Scotland, resolved to try to improve the efficiency of "molecular farming," the genetic engineering of animals to produce valuable human proteins such as blood clotting factors. Animals were then being engineered for the purpose by injecting the gene for the protein into newly fertilized eggs that a surrogate mother brought to term. The gene generated the desired protein in only about 5 percent of the resulting animals. But if those animals could be cloned, the 95-percent failure rate could be turned into a 100-percent success rate. That prospect brought Wilmut support for his research from PPL Therapeutics, a biotechnology firm.

Wilmut thought that adult cells might be clonable if the nucleus was taken from cells in the right condition. Keith Campbell, an embryologist whom he hired to assist him in the research, suggested that cells in the G0 condition—a state of quiescence they enter when near starvation—might do. They confirmed this possibility in March 1996 when two lambs were born that they had cloned, using the G0 approach, from differentiated embryo cells. They then attempted to clone a sheep from adult udder cells. The effort produced 277 failures and one success—a sheep, born in July, that they named Dolly, in honor of the singer and actress Dolly Parton. "No one could think of a more impressive set of mammary glands than Dolly Parton's," Wilmut explained.

The announcement of Dolly's birth the following February—it was delayed to give PPL Therapeutics time to file a patent on the cloning technology—prompted immediate international debate about the application of cloning to human beings. Opponents demanded that it be legally banned. They prevailed in several countries, but not absolutely, since the biotechnology industry and many biomedical scientists backed human cloning for research purposes. Proponents see in cloning opportunities to study cellular differentiation and development and to obtain human stem cells for medical purposes.

D. J. Kevles

CLOUD AND BUBBLE CHAMBERS. C. T. R. Wilson built the first cloud chamber in 1895 to satisfy his interest in the weather. Previous work by John Aitken had examined the role of dust as a nucleating agent for water vapor in air, and hence as a source of fog and clouds. Like Aitken, Wilson built a chamber to reproduce in the laboratory the condensation of clouds: sudden expansion of the volume of a closed vessel containing saturated air produced a temperature drop and supersaturated the air. Unlike Aitken, Wilson brought a background in physics and the program of the Cavendish Laboratory at Cambridge University, especially in ion physics and discharge tubes, to bear on the subject. Instead of dust, Wilson focused on the role of ions as nuclei for water droplets. He also began photographing the formation of drops. Then in 1910 Wilson thought to use the device as a detector of charged particles, whose passage through the chamber would leave a trail of ions and hence water droplets. The next year Wilson obtained his first photographs of the tracks left by alpha and beta rays, as well as evidence of X and gamma rays through the beta rays they produced, and thus provided compelling visual evidence of individual atoms and electrons and their interactions.

The cloud chamber then became a popular tool for the study of particles given off by radioactivity, nuclear physics, and cosmic ray physics. Commercial firms helped propagate the device by providing affordable, experiment-ready Wilson chambers. P. M. S. Blackett, also at the Cavendish, used a Wilson chamber in the early 1920s to confirm Ernest Rutherford's transmutation of nitrogen into oxygen. In the early 1930s Blackett and Giuseppe P. S. Occhialini built a countercontrolled chamber, with a Geiger counter wired to trigger the expansion of the chamber whenever a cosmic ray passed through it. They used the chamber in 1932 to confirm the existence of the positron, which Carl Anderson of the California Institute of Technology (Caltech) had just detected in his own cloud chamber.

The Wilson cloud chamber suffered from a slow cycle time, and its diffuse gas offered few chances for interaction with incoming particles. The solid film of nuclear emulsions yielded more interactions and hence grew in popularity in the 1930s; but emulsions also constantly recorded tracks and hence complicated the resolution of occurrence times. In 1952, Donald Glaser, a physicist at the University of Michigan, tried to solve these problems by turning to a liquid analogue of the cloud chamber: instead of supersaturated gas, Glaser used a superheated liquid. He filled a small glass bulb, a couple of centimeters wide, with liquid diethyl ether held under pressure above its boiling point, then suddenly released the pressure, superheating the liquid. A charged particle passing through the chamber further heated the liquid and left a line of vapor bubbles in its wake. A high-speed camera filmed the first tracks in late 1952, and Glaser announced his results in 1953.

Glaser's bubble chamber provided sufficient density for numerous interactions and a fast cycle time. He intended to use his bubble chamber to detect cosmic rays and hence tried various means of triggering the expansion as Blackett had done with the cloud chamber. The bubble chamber instead became an important particle detector for high-energy accelerators, whose predictable output dispensed with the need for countercontrolled expansion. A particular implication of the bubble chamber intrigued accelerator physicists: the possibility of using liquid hydrogen, which, because of its simple nucleus, already served as a target for interaction experiments at accelerators. A hydrogen bubble chamber would combine target and detector in one device.

Accelerator laboratories soon began building bubble chambers, including a group at the University of California at Berkeley under Luis Alvarez. The Berkeley group produced the first tracks in a hydrogen chamber in late 1953 and soon scaled up to larger chambers, culminating in a 180-cm. (72-in.) version to accommodate the greater interaction lengths of hyperons and other strange particles. The massive chamber, completed in 1959, presented new problems in cryogenics, optical systems, and computerized data analysis. The coordination of the physicists, engineers, and technicians building the chamber produced a complex, corporate organizational structure.

The Berkeley bubble chamber signaled the growing importance accorded the detector in accelerator experiments. It also marked a decisive shift from the table-top device of Glaser, built for cosmic-ray physics, to the big science of high-energy physics. Bubble chambers at several accelerator laboratories paid dividends in evidence of new particles and resonances that supported the SU(3) theory for classifying strange particles in the early 1960s and of neutrino interactions that helped confirm the electroweak theory in the early 1970s. Both Glaser and Alvarez won Nobel Prizes in physics for their work with bubble chambers, and both eventually drifted away from the field, disillusioned with the routinization, specialization, and automation that the bubble chamber had brought to particle detection.

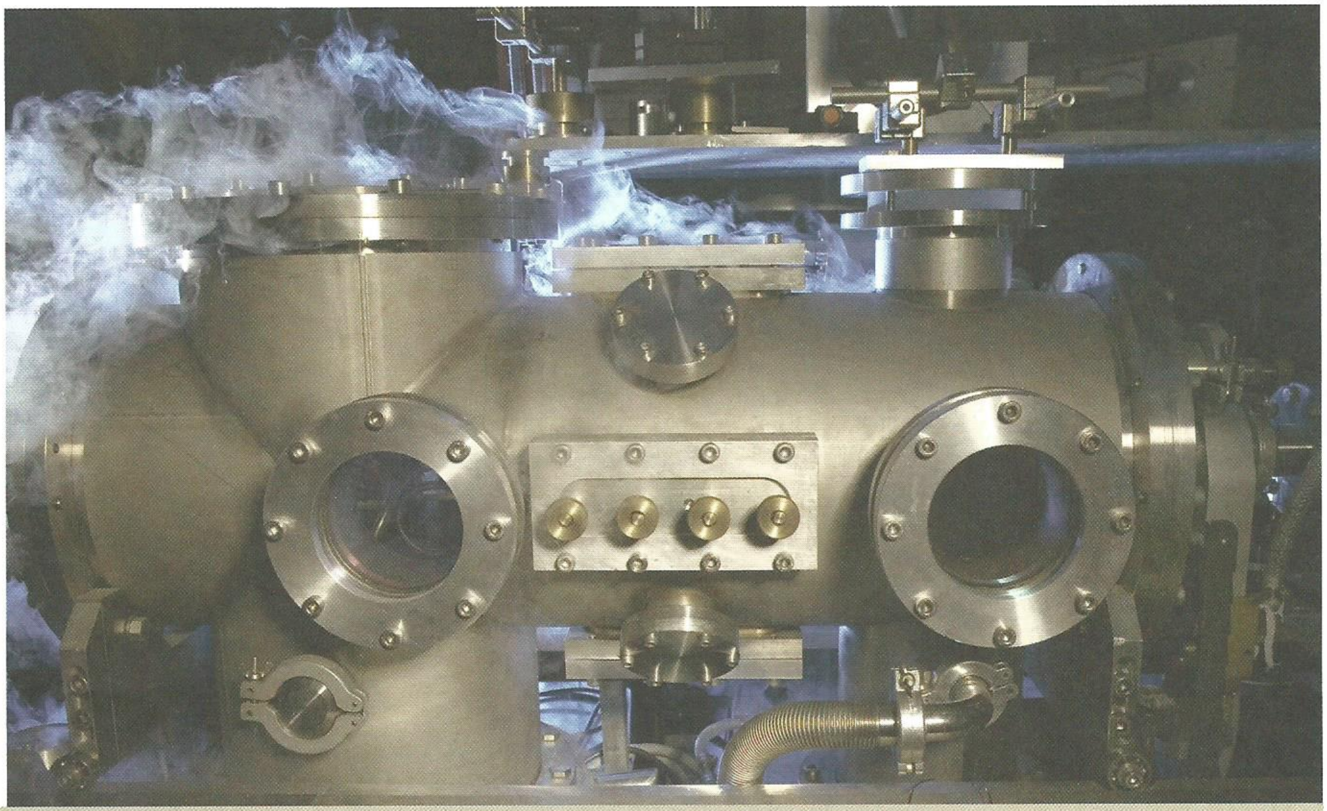
PETER J. WESTWICK

COLD AND CRYONICS. Artificially produced cold has always been welcome. From the time ice was brought from the mountains so that the Roman emperors could enjoy their wine chilled in the summer to our days of high temperature superconductivity, the wonders of low temperatures have been publicly displayed and their benefits privately pursued. From unexpected phenomena of the very cold to dramatic changes in food production and eating habits, the production and harnessing of cold has probed nature and shaped society.

The first systematic researches on cold were reported by Robert Boyle in his *New Experiments Touching Cold* (1665)—the subject that the master of experimenters found "the most difficult" of all. The ingenious experiments of Joseph Black to determine the latent heat and specific heat of water involved ordinary ice. Cryogenics received a boost from Michael Faraday's liquefaction of nearly all the gases known in the 1820s. Among the gases he could not liquefy were oxygen, nitrogen, and hydrogen. By the end of the nineteenth century all gases except helium had been liquefied. Raoul-Pierre Pictet in Geneva and Louis Paul Cailletet in Paris first obtained small droplets of oxygen and nitrogen in 1877. Zygmunt Florenty von Wróblewski and Karol Stanisław Olszewski liquefied oxygen in appreciable quantities in 1883. Carl von Linde and William Hampson made significant improvements to the apparatus for reaching low temperatures. James Dewar liquefied hydrogen in 1898 at the Royal Institution in London. Heike Kamerlingh Onnes managed to liquefy helium on 10 July 1908 at the Physical Laboratory of the University of Leiden. Using the regeneration method and starting from liquid hydrogen temperatures, he made liquid helium and found its boiling point to be 4.25°K and its critical temperature 5°K.

The development of thermodynamics, especially James Prescott Joule's and William Thomson's proofs that the temperature of a gas dropped when it expanded very quickly, provided the necessary background for the investigation and the understanding of the properties of matter in the very cold. Thomas Andrews's experiments determining the critical point—the temperature at which a gas whose pressure is increased at constant volume liquefies—and Johannes Diderik van der Waals's discussion of the continuity of the gaseous and liquid states brought further insight into the characteristics of very cold fluids.

The nineteenth century saw remarkable developments in the large-scale production of cold, especially through the development of the vapor compression process that led to different types of refrigerating machines and refrigeration processes. The plentiful availability of artificial cold transformed the preservation, circulation, and consumption of food. By the end of the nineteenth century the Linde Company had sold about 2600 gas liquefiers: 1406 were used in breweries, 403 for cooling land stores for meat and provi-



Apparatus at the Laboratoire Kastler Brossel, Paris, for producing liquid helium to create a Bose-Einstein condensate, a state of matter near absolute zero in which many atoms act like one

sions, 204 for cooling ships' holds for transportation of meat and food, 220 for ice making, 73 in dairies for butter making, 64 in chemical factories, 15 in sugar refining, 15 in candle making, the rest for other purposes.

In 1911, the Institut International du Froid was founded in Paris to regulate the industry and to formulate directions of further research on cold. The preservation and transport of agrarian, fish, and dairy products, the standardization of the specifications for home refrigerators, the construction of trains and ships with large refrigerators, the installation of special refrigerators in mortuaries and slaughterhouses, the building of new hotels with air cooling systems, the design of breweries, the manufacture of transparent ice, and the possibilities of medical benefits from cold were some of the issues on which the national delegates who founded the Institut reached consensus.

In 1911, Kamerlingh Onnes observed that certain metals become superconductors, losing all resistance to electrical current, below 4°K. In recent decades materials have been made that reach the superconducting state at much higher temperatures. Another bizarre bit of cold behavior, which came to light in the 1930s, is the superfluidity that liquid helium acquires below 2.19°K in virtue of which it does not display any of the features of classical fluid. These two phenomena turned out to be explicable only on the principles of quantum mechanics. The explanation forced quantum mechanics to negate one of its basic methodological and historical tenets—that it made a difference only in the microscopic world. Superconductivity and superfluidity showed that macroscopic quantum phenomena exist.

With the availability of liquefied gases, the variation of the electrical resistance of metals with temperature was persistently studied. Dewar and John Ambrose Fleming made the first systematic measurements in 1896. Their results derived at liquid oxygen temperatures suggested that electrical resistance would become zero at absolute zero. But the same measurements at liquid hydrogen temperatures showed that the resistances after reaching a minimum started increasing again. In 1911, Kamerlingh Onnes measured the resistance of platinum and that of pure mercury at helium temperatures. At 4.19°K the value of the resistance dropped abruptly and became 0.0001 times that of solid mercury at 0°C. Impurities did not affect the superconductivity of mercury, but a high magnetic field could destroy it.

The first successful quantum mechanical theory of electrical conduction, proposed by Felix Bloch (1928), predicted that superconductivity was impossible. This theory considers the electrons in a metal as uncoupled, though it calculates the field in which any one electron moves by averaging over the other electrons. If the metal was at absolute zero, its immobile lattice determined a periodic potential field for the electronic motions and offered no electrical resistance. Bloch used an analogy to ferromagnetism to try to understand superconductivity. He found that the most stable state of a conductor, in the absence of an external magnetic field, had no currents. But since superconductivity was a stable state displaying persistent currents without external fields, his theory did not explain how superconductivity could come about in the first place.

At the beginning of November, 1933, there appeared a short letter in *Naturwissenschaften* by Walther Meissner and Robert Ochsenfeld. It presented strong evidence that, contrary to every expectation and belief of the previous twenty years, a superconductor expelled the magnetic field after the transition to the superconducting state and the magnetic flux became zero (the Meissner effect). Superconductors were found to be diamagnetic and, hence, superconductivity a reversible phenomenon, thus allowing the application of thermodynamics.

In 1934, Fritz London and his brother Heinz, on the assumption that diamagnetism must be an intrinsic property of an ideal superconductor, and not merely a consequence of perfect conductivity, proposed that superconductivity involved a connection not with the electric, but with the magnetic field. Their assumption led to the electrodynamics of a superconductor consistent both with the zero resistance and the Meissner effect. Fritz London, in his discussion of superconductivity in 1936, formulated for the first time the notion of a macroscopic quantum phenomenon.

Because ionic masses are so much larger than the electron mass, physicists doubted that ions played an important role in the establishment of the superconducting state. Herbert Frohlich in 1950 asserted the opposite and found that the interaction of the electrons in a metal with the lattice vibrations would lead to an attraction between the electrons. Experiments confirmed his assertion. The mass became an important parameter when the motion of the ions was involved, and this, in turn, suggested that superconductivity could be derived from an interaction between the electrons and zero-point vibrations of the lattice. Soon after learning about these results, John Bardeen showed that superconductivity might arise from a new attraction between the electrons and the phonons resulting from lattice vibrations, thus laying the foundations for the electron pair theory. In 1956, Leon Cooper argued that such an interaction could provide what was needed. Based on these ideas, in 1957 Bardeen, Cooper, and John R. Schrieffer worked out the details of a microscopic theory of superconductivity, and shared the Nobel Prize in physics of 1972 for their successful explanation of this elusive phenomenon.

All liquids solidify under their own pressure at low enough temperatures. Helium can only be solidified under a pressure of 26 atmospheres. The densities and specific heats of all liquids follow a continuous change and increase as the temperature goes down. In the case of helium, however, these parameters display a maximum at 2.19°K and then decrease. The two methods for measuring the viscosity of any liquid—rotating a disk in it or forcing it through very small capillaries—give identical results. Not so for liquid helium below 2°K. The first of these methods gives a value a million times larger than the second. Finally, all liquids can be deposited in open containers, kept in containers with extremely small holes through which they cannot flow, and remain at rest when exposed to light. Liquid helium does not tolerate any such constraints. It goes over open containers, leaks through the smallest capillaries, and springs up in a fountain when light falls on it. Below 2.19°K liquid helium becomes a superfluid.

In 1938, Fritz London proposed that the transition to the superfluid state can be understood in terms of the Bose-Einstein condensation mechanism, first discussed by Albert Einstein in 1924. For an ideal Bose-Einstein gas, the condensation phenomenon represented a discontinuity in the derivative of the specific heat. London argued that the sudden changes in the properties of helium at 2.19°K could result from such discontinuities. Below a certain temperature and depending on the mass and density of the particles, a finite fraction of them begins to collect in the energy state of zero momentum. The remaining particles fly about as individuals, like the molecules in a normal gas. Laszlo Tisza proposed to regard superfluid helium as a mixture of a normal and a superfluid. These two components had different hydrodynamical behaviors as well as different heat contents. At absolute zero, the entire liquid became a superfluid consisting of condensed atoms, while at the transition temperature the superfluid component vanished.

Excluding some applied fields, low-temperature physics became the high point of Soviet physics, especially during World War II. After receiving his doctorate under the supervision of Ernest Rutherford, Pyotr Kapitsa served as an Assistant Director of magnetic research at the Cavendish Laboratory, before becoming the director of the Mond Laboratory in Cambridge. There he liquefied helium in 1934. Though he was not allowed to return to England by the Soviet authorities after a trip in 1934, he was, by 1935, appointed as director of a new Institute of Physical Problems within the Academy of Sciences in Moscow. That is where he conducted his experiments with liquid helium in 1941 and coined the term "superfluid" when he discovered the remarkable characteristics of its viscosity. In 1941, Lev Landau developed a quantized hydrodynamics that explained the transition to the superfluid state in terms of rotons and phonons. The ground states and the excitations played the roles of the superfluid and normal state, respectively. The excitations were the normal state because they could be scattered and reflected and, hence, exhibit viscosity. The ground state described the superfluid because it could not absorb a phonon from the walls of the tube or a roton unless it met some conditions on the velocity. Landau's formalism led to two different equations for the velocity of sound. One was related to the usual velocity of compression, while the other depended strongly on temperature. Landau named it "second sound." Victor Peshkov demonstrated the existence of standing thermal waves in 1944 for the first time, and in 1949 the experiments of Maurer and Herlin settled the issue of the temperature dependence of the second sound velocity below 1°K. By 1956, Richard Feynman could show that some of Landau's assumptions could be justified quantum mechanically and that the rotons were a quantum mechanical analog of a microscopic vortex ring.

Kostas Gavroglu

COLLIDER. During the final quarter of the twentieth century, particle colliders emerged as the preferred instruments in high-energy physics. Their defining characteristic, besides their great size—the largest are measured in kilometers—is their manner of generating collisions. They accelerate two beams of subatomic particles and bring them together at interaction points, where a particle in one beam can collide with a particle in the other. Surrounding each interaction point, a particle detector records the tracks, energies, and other characteristics of particles emanating from these collisions, allowing physicists to analyze what transpired.

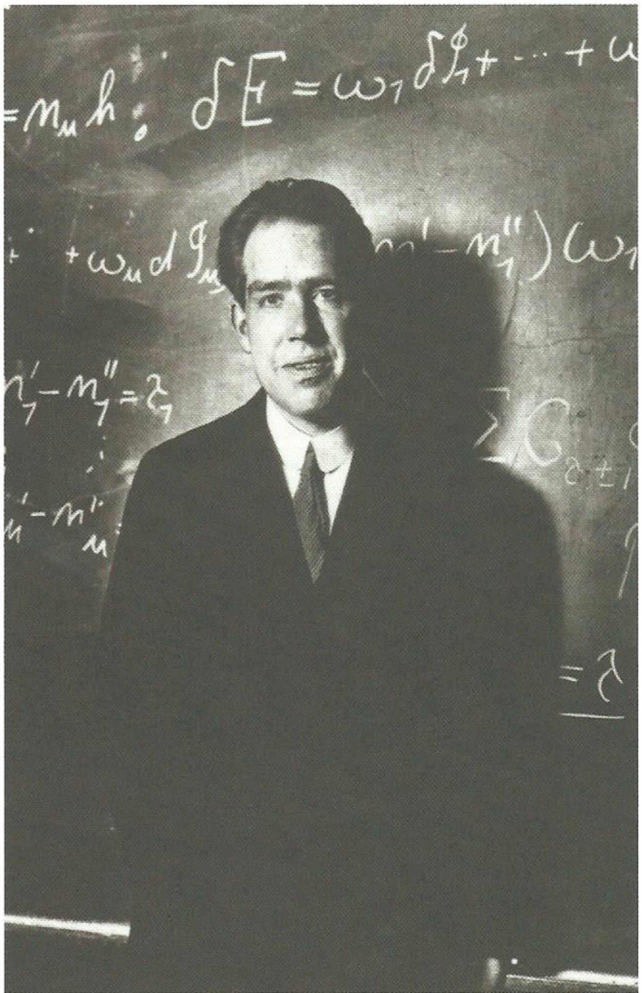
The great advantage of colliders over conventional "fixed-target" machines (such as cyclotrons), in which particle beams strike stationary objects, is that essentially all the energy of the individual colliding entities can be used to create new subatomic particles. The available "center-of-mass" energy, or total collision energy, grows in proportion to the beam energy rather than to its square root, as in fixed-target experiments. All discoveries of massive new subatomic particles since 1975 have been made using colliders, while fixed-target experiments have excelled at examining the structures of known particles such as protons. To permit meaningful experiments, colliders must attain sufficient luminosity, a key measure of the rates of interaction between particles in the opposing beams.

The idea of particle colliders occurred to Rolf Wideröe and Donald Kerst in the mid-1950s, but the first significant work on developing such an instrument began at Stanford University in 1958. Led by Gerard O'Neill of Princeton University, a small group of physicists built two evacuated "storage rings" in a figure-eight configuration. Beams of electrons circulated in opposite directions within these rings at energies of up to 500 million electron volts (MeV); collisions occurred in the shared segment where the rings touched.

In parallel with this effort, physicists at the Frascati National Laboratory in Italy, led by Bruno Touschek, built a single-ring collider in which electrons circulated one way and positrons (their antimatter opposites) the other. Following the success of this prototype, the Italian physicists developed a full-scale electron-positron collider called ADONE, with beam energies of up to 1,500 MeV, or 1.5 billion electron volts (GeV). Experiments using this instrument began in 1968, recording electron-positron annihilations that usually created other subatomic particles.

Physicists at the European Center for Nuclear Physics (CERN), led by Kjell Johnsen, pioneered proton-proton colliders. In 1971, they successfully operated the Intersecting Storage Rings, in which beams of protons circulated at energies of up to 28 GeV. Collisions occurred at six interaction points where the interlaced rings crossed.

The most productive electron-positron collider was the SPEAR facility built at the Stanford Linear Accelerator Center (SLAC) under the direction of Burton Richter. Completed in 1972, SPEAR generated collisions at combined energies of up to 8 GeV. It yielded the discoveries of the massive psi particles and tau lepton, and Nobel Prizes for Richter (in 1976) and SLAC physicist Martin Perl (in 1995).



Danish theoretical physicist Niels Bohr (1885–1962) photographed around 1920

Following these advances, physicists built colliders at all leading high-energy physics laboratories. Especially noteworthy was a proton-antiproton collider built at CERN as an upgrade of its existing Super Proton Synchroton, stimulated by ideas and inventions of Peter McIntyre, Carlo Rubbia, and Simon Van der Meer. By observing proton-antiproton collisions at total energies of up to 540 GeV in 1982–1983, two teams of physicists discovered the massive W and Z bosons, the mediators of weak interactions and key elements of the standard model.

These significant discoveries and the development of superconducting magnets for the Tevatron proton-antiproton collider at the Fermi National Accelerator Laboratory (Fermilab) encouraged U.S. physicists to design the Superconducting Super Collider (SSC), a 40,000 GeV proton-proton collider that was to have a circumference of 86 km (54 miles), several interaction points, and a cost of $5.9 billion. Those were its parameters in 1989 when construction began south of Dallas, Texas. Congress terminated the project in 1993 owing to cost overruns, lack of major participation from other countries, and a concern to reduce budget deficits after the Cold War.

Since the SSC's demise, the development of particle colliders has continued largely through upgrades of existing instruments at CERN, Cornell University, Frascati, Fermilab, and SLAC, and at national laboratories in China and Japan. A prime example was the conversion of the Stanford Linear Accelerator into a linear electron-positron collider. The new machine accelerated individual "bunches" of the two types of particle and brought them together after a single pass through the linear accelerator. This approach contrasts with that of storage-ring colliders, in which the bunches of particles circulate continuously in fixed, intersecting orbits.

MICHAEL RIORDAN

COMPLEMENTARITY AND UNCERTAINTY constitute the foundation of the "Copenhagen interpretation" of quantum physics, an acausal understanding of physics that remains predominant today. Both concepts were introduced in 1927, by Niels Bohr and Werner Heisenberg, respectively. They arose as part of the development of quantum physics when the field was in tremendous flux. Several institutions—notably the Bohr Institute for Theoretical Physics and the physics institute at the University of Göttingen—and many individual physicists had placed high stakes on establishing an acceptable theory as well as its interpretation.

Bohr had been a leader in the development of quantum physics since he published his revolutionary atomic model in 1913. In Bohr's model, atomic electrons could exist only in orbits determined by the quantum of action and emit electromagnetic radiation only when jumping from one orbit to another. During the "old quantum theory" (1913–1925), theorists invoked a mixture of Bohr's "correspondence principle" (which specified a numerical connection between quantum and classical physics) and arguments based on the quantum of action. As one of a long line of increasingly radical attempts to arrive at an overarching theory, in 1924 Bohr, his assistant Hendrik Kramers, and an American postdoctoral researcher, John Slater, published a paper based on a denial of the well-established principle of energy conservation. In their view, the principle held only statistically and not for individual atomic processes. Experimental results showing energy conservation in collisions between individual photons and atomic electrons in the Compton effect quickly forced the abandonment of this view, and others took the lead in seeking to formulate a quantum theory. In the fall of 1925, Heisenberg, then working as Bohr's assistant, devised a means to calculate spectral data without explicit appeal to the correspondence principle. Whereas Heisenberg's severely operationalist, as well as particle-oriented, theory involved complicated matrix calculations, Erwin Schrödinger's wave-oriented version of "quantum mechanics," published in the fall of 1926, involved mathematics with which the average physicist felt more comfortable. In spite of this, and although Schrödinger's "wave mechanics" seemed at first to allow the visualization of atomic processes by emphasizing continuity and retaining causality, Schrödinger and others soon showed that his approach was mathematically equivalent to Heisenberg's.

In September 1926, Schrödinger paid a now famous visit to Copenhagen. Bohr stubbornly sought to convince him of the reality of quantum jumps. In this tense environment Heisenberg wrote the article containing his "uncertainty principle," which stated that in the atomic domain the quantum of action set a limit to the precision with which two conjugate variables, such as a particle's position and momentum, or the time and energy of an interaction, could be measured. Since the present therefore cannot be fully specified, Heisenberg argued, neither can the future. By explaining the indeterminism of quantum physics in this way, Heisenberg tried to make his presentation more visualizable *(anschaulich)* and hence more acceptable to his fellow physicists.

Heisenberg overstepped common practice by submitting his article from Copenhagen without asking Bohr's permission. It turned out that Bohr disagreed so strongly with Heisenberg's presentation of the quantum that Heisenberg felt compelled to add a correction in the proofs that allowed a greater role for the wave picture. Bohr was then perfecting his own formulation of the foundations of quantum theory. At the end of a lecture surveying the general situation given in Como in September 1927, he proposed his notion of complementarity for the first time. The new notion provided an understanding of quantum mechanics in general and of Heisenberg's uncertainty principle in particular. Bohr maintained that, unlike in classical theory, a description of processes in space-time and a strictly causal account (by which Bohr meant an account recognizing conservation laws) of physical processes excluded one another. This meant in practice that the investigator could choose which aspect of microphysical reality he wished to see expressed by his choice of experimental setup. Although the setup required for realizing one aspect excluded the realization of the other—for example, an apparatus for exhibiting light with particulate properties cannot also show it as a wave—both sets of properties had to be invoked to obtain a complete description of the microphysical reality. While presented as a direct result of quantum mechanics, Bohr's interpretation and his subsequent elaborations of it resonated with philosophical views with which he had struggled in his youth. Only with Bohr's complementarity of 1927 did his work and that of Heisenberg, Max Born, Wolfgang Pauli, Pascual Jordan, and others begin to converge into what came to be seen as the unified "Copenhagen interpretation" of quantum mechanics.

The group surrounding Bohr soon came to perceive complementarity and uncertainty as so closely intertwined that in 1928 Heisenberg gave Bohr's concept precedence over his own. In 1935, Albert Einstein and two collaborators challenged Bohr's interpretation for being inherently incomplete; they thought that they could obtain more information by experiment than complementarity allowed. Bohr repelled their attack by widening the divide between classical and quantum ideas. In the larger physics community, however, the uncertainty principle became inseparable from any presentation of quantum mechanics, while complementarity figured little in the teaching of the new physics. It tended to be regarded as overly philosophical, vague, and irrelevant.

In recompense, complementarity took on a life beyond physics. Bohr sought to generalize its application, first to psychology, then to biology, and ultimately beyond the scope of natural science. Although he did not complete the book on the topic that he had hoped to write, Bohr conceived complementarity as a general epistemological argument of great import for humanity. It constituted a guiding principle for his own activities, inside and outside physics. At the same time, Bohr's disciples sought to spread their understanding of Bohr's word, sometimes—as in the case of Jordan, who tried to use it to save the freedom of the will—to Bohr's embarrassment. Variations of complementarity became part of severe ideological struggles in Nazi Germany and the Soviet Union.

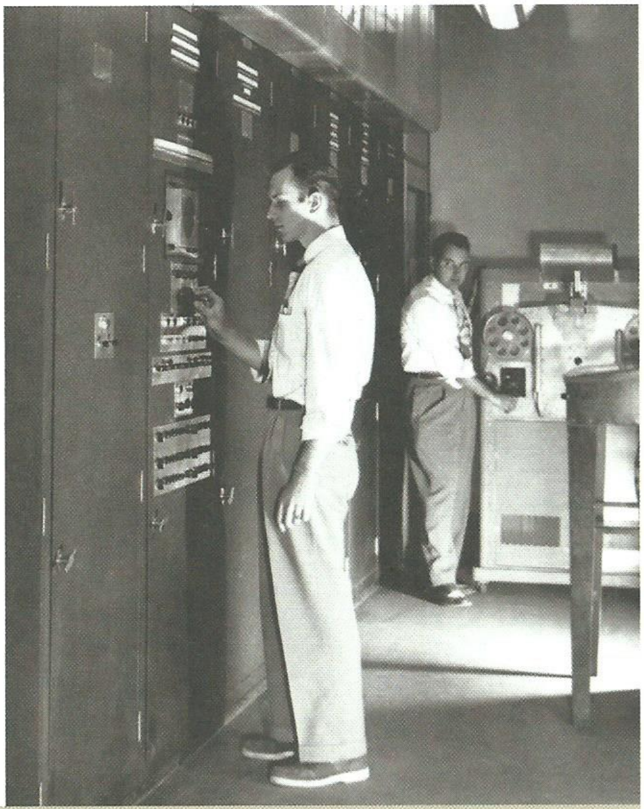
While extremely devoted, the audience for Bohr's philosophical statements was never large, and today consists largely of a specialized set of philosophers. Nevertheless, complementarity played an important role in providing a conceptual basis for the early work on quantum mechanics.

FINN AASERUD

COMPUTER SCIENCE. Computer science is the study of the principles and the use of devices for the processing and storing of usually digital data using instructions in the form of a program. Before the existence of modern computers, people who performed calculations manually were known as "computers." The term "computer science," signifying a particular combination of applied mathematics (particularly logic and set theory), and engineering (normally electronic) first occurred as the name of a university department at Purdue (U.S.) in 1962. The two key areas of development have been hardware (the computers themselves) and more recently software (the intangible programs that run on them).

Mechanical computing devices long preceded electronic ones. The earliest known mechanical adding machine, the creation of the German inventor Wilhelm Schickard, dates from 1621. The mechanical calculators created by Blaise Pascal (1623–1662) and Gottfried Leibniz (1646–1716) received wider attention than Schickard's machine, which fell into oblivion, and formed part of the intellectual inheritance of Charles Babbage (1792–1871), often celebrated as a pioneer of computing. Alarmed by the number of mistakes in hand-computed mathematical tables, he invented the Difference Engine and subsequently the Analytical Engine with many of the features of a modern computer. The "mill" (the gears and wheels that performed the arithmetical operations) corresponded to a modern central processing unit (CPU) for computation and the "store" was a mechanical memory for reading and writing numerical values. Ada Lovelace (1815–1852), the daughter of Lord Byron, provided the earliest comprehensive description of this first programmable computer partially based on notes by the Italian Luigi Menabrea (1809–1896). Babbage never completed the Analytical Engine, which would have stretched cogwheel machinery to its limits at the time.

Leibniz was the first mathematician thoroughly to study the binary system, upon which all modern digital comput-



Technician working on EDVAC, an improvement of ENIAC and, like it, intended for ballistic calculations. ENIAC operated from 1951 to 1961 at the University of Pennsylvania.

ers are based. George Boole presented what became known as Boolean algebra or logic in his masterwork of 1854, *An Investigation of the Laws of Thought.* Boole's laws can be used to formalize binary computer circuits. Later, David Hilbert (1862–1943) argued that in an axiomatic logical system all propositions could be proved or disproved, but Kurt Gödel (1906–1978) demonstrated otherwise, with important implications for the theory of computability. Propositional and predicate logic, together with set theory, as formulated by Ernst Zermelo (1871–1953) and Adolf Fraenkel (1891–1965) among others, provide important underpinnings for computer science.

Analog computers use continuous rather than discrete digital values. They enjoyed some success before digital technology became established for systems of related variables in equational form. Vanne var Bush devised the successful Differential Analyzer for solving differential equations at the Massachusetts Institute of Technology during the 1930s. Later he wrote a seminal article, "As We May Think" (1945), that predicted some of the features of the World Wide Web, illustrating a very broad appreciation of computer science.

In 1936, the English mathematician Alan Turing, influenced by Gödel, devised a theoretical "universal machine," later known as a Turing machine, that helped to define the limits of possible computations on any computing machine. Turing had a practical as well as a theoretical bent. He played a significant part in the building of Colossus, at Bletchley Park, which made possible the breaking of German codes during World War II. Although it has a claim to be the first modern digital computer, Colossus had little influence since it remained secret for several decades. Turing subsequently worked on the design of the Pilot ACE computer at the National Physical Laboratory and the programming of the Manchester Mark I at the University of Manchester, both successful postwar British computers. Turing's standing in modern computing is indicated by the Turing Award, computer science's highest distinction. It has been given annually since 1966 by the Association for Computing Machinery (ACM), the subject's foremost professional body, founded in 1947.

John Atanasoff built what may have been the first electronic digital computer, the Atanasoff-Berry, prototyped in 1939 and made functional in 1940. It influenced John Mauchly, who with J. Presper Eckert constructed the famous ENIAC at the Moore School of Electrical Engineering in Philadelphia between 1943 and 1945. EDVAC, the first U.S.-built stored-program computer, followed in 1951. Maurice Wilkes attended a summer program at the Moore School in 1946, returned to the University of Cambridge in England, and completed the EDSAC in 1949. Its run on 6 May 1949 made it the world's first practical electronic stored-program computer. The Lyons company copied much of EDSAC to produce the first commercial data processing computer, the LEO (Lyons Electronic Office), in 1951. Other important early computer pioneers include Konrad Zuse, who worked separately on mechanical relay machines, including floating-point numbers, producing the Z1-Z4 models in Berlin between 1936 and 1945. Significant U.S. engineers include Howard Aiken, who developed the electromechanical calculator Harvard Mark I, launched in August 1944, and George Stibitz, who illustrated remote job entry in September 1940 by communicating between Dartmouth College in New Hampshire and his Model 1, first operational in 1939, located in New York. Aiken established programming courses at Harvard long before the university computer science courses of the 1960s.

Programming facilities for early computers initially operated at the binary level of zeros and ones. Assembler programs allowed the input of instructions in mnemonic form, but still matching the machine code very closely. Higher-level programming less dependent on machine language requires a compiler program run on a computer. Noam Chomsky provided influential formal characterizations of grammars for languages, including programming languages, in the late 1950s and early 1960s.

Early high-level programming languages for scientific and engineering applications included Fortran, developed between 1954 and 1957 by John Backus and others at IBM in New York City. Backus also devised Backus Normal Form (BNF) for the formal description of the syntax of programming languages. Successive versions of Fortran have kept it in use. COBOL was another important programming language, developed for business applications in the late 1950s. U.S. Navy Captain Grace Hopper played a key part in its creation. ALGOL, the first programming language described using BNF, included in its 1960 version important new features such as block structuring, parameter passing by name or value, and recursive procedures that greatly influenced subsequent programming languages.

Pascal, designed by Nichlaus Wirth in Zurich between 1968 and 1970, embodied the concepts of structured programming espoused by Edsger Dijkstra and C. A. R. Hoare. Its simplicity suited it for educational purposes as well for practical commercial use. Wirth went on to develop Modula-2 and Oberon and is widely considered as the world's foremost designer of programming languages. Ada was developed in the 1970s for U.S. military applications. It proved to be the opposite of Pascal in the scale of complexity.

Dennis Ritchie created "C" as a general-purpose procedural language. It served as a basis for the highly influential Unix operating system, developed by Ritchie and Kenneth Lee Thompson at Bell Laboratories in New Jersey and refined still further there into C++. C++ encourages information hiding, as suggested by David Parnas, or encapsulation within "objects" considered as instances of classes, a technique first used in the SIMULA language, produced by Ole-Johan Dahl and others in 1967. The highly successful language Java, designed as a portable object-oriented programming language for distributed applications, dates from the early 1990s.

The languages so far considered follow an order of instructions. Some higher-level languages, such as LISP (late 1950s and early 1960s, at MIT), widely used in artificial intelligence, express computations in the form of mathematical functions, and so reduce the importance of the ordering of execution. Logic programming, as in Prolog (1970s), is a relational approach admitting nondeterministic answers. An extension, constraint logic programming, allows the convenient inclusion of extra conditions on variables.

A von Neumann machine, similar but not identical to a theoretical Turing machine, refers to the standard arrangement of early sequential computers with CPU and memory still widely used. However, parallel architectures have become increasingly important, as computer-processing power presses against physical limits. Architecture has evolved through valves or tubes, solid-state transistors, and integrated circuits of increasing complexity.

Theoretical underpinnings for computer science include the definition of computability incorporated in the Turing machine, the λ-calculus of Alonso Church (1903–1995), and recursive functions. Complexity theory aids reasoning about the efficiency of computation. Other theoretical computer science subdisciplines include automata theory, computational geometry (for computer graphics), graph theory, and formal languages.

Software engineering encompasses the process of producing programs from requirements and specifications via a design process. Dijkstra from Holland has been a major contributor to the field. His influential paper *GO TO Statement Considered Harmful* (1968) led to the acceptance of structured programming, a term he coined, in the 1970s, in which abstraction is encouraged in the design process and program constructs are limited to make reasoning about the program easier. Dijkstra, Dahl, and Hoare wrote the widely read *Structured Programming* (1972). Hoare has also made important contributions to formal reasoning about programs using assertions, sorting algorithms, and the formalization of concurrency. Donald Knuth of Stanford University has been a major innovator in computer algorithms. His multivolume and still unfinished magnum opus, *The Art of Computer Programming,* is one of the best-known and influential books in computer science. He has contributed especially to parsing, reasoning, and searching algorithms, all important computer science techniques. Like all good computer scientists, he has expertise in both theory and practice. As well as major theoretical contributions, he has produced the TeX document preparation system, still widely used by computer scientists internationally for the production of books and papers.

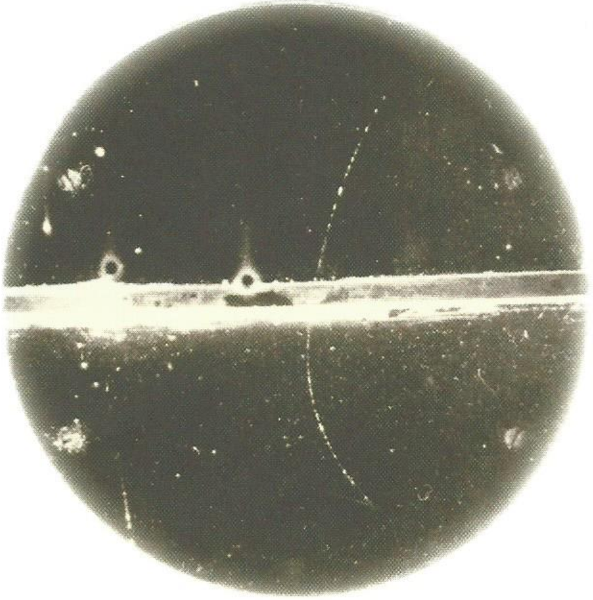
Artificial intelligence (AI) has held out huge promises that have been slower to mature than expected. Major contributions have been made by John McCarthy, latterly at Stanford University, and Marvin Minsky at MIT. Important aspects of AI include automated reasoning, computer vision, decision making, expert systems, machine learning, natural language processing, pattern recognition, planning, problem solving, and robot control. A successful outcome of the Turing test, where the responses of a human are essentially indistinguishable from those of a computer, has proved elusive in practice unless the knowledge domain is very limited. Connectionism, using massively parallel systems, has opened up newer interesting areas for machine learning such as neural networks (similar to the workings of the brain) and also genetic algorithms (inspired by Darwin's theory of evolution). Databases are an important method of storing, organizing, and retrieving information. The Briton Edgar Codd created the relational model for databases in the late 1960s and early 1970s at the IBM Research Laboratory in San Jose, California. The two important categories of database objects are "entities" (items to be modeled) and "relationships" (connections between the entities) for which a good underlying theory has been established. Communication has become as significant as computation in computing. Claude Shannon provided an important theoretical approach in his paper of 1948, *A Mathematical Theory of Communication.* He contributed to both network theory and data compression. Donald Davies of NPL and others developed packet switching in the 1960s, a precursor to the Internet, originally established in 1969 and known as the ARPAnet for many years. More recently, the expansion of the Internet has made possible the proliferation of the World Wide Web (WWW), a distributed information system devised in the early 1990s by the British scientist Tim Berners-Lee at CERN in Switzerland. His unique insight combined a number of key principles: a standard network-wide naming convention for use by hyperlinks in traversing information; a simple but extensible markup language to record the information; and an efficient transfer protocol for the transmission of this information between the server and a client user.

Computer science has had an enormous social impact in recent years. Yet it is still a relativity young and perhaps immature science. Quantum computers offer the possibility of removing some of the stumbling blocks encountered today and could theoretically render useless many of the data security mechanisms currently in place. The future of computer science looks even more interesting than its past.

JONATHAN P. BOWEN

CONSERVATION LAWS. Isolated physical and chemical systems possess certain unchanging properties, for example, mass and energy, and, if in thermal equilibrium, temperature. Conservation laws refer to a subset of these properties conserved when these systems interact (conservation of energy, conservation of mass). Natural philosophers first explicitly set out such rules in the eighteenth century. Conservation laws have guided theory in the physical sciences ever since. Many instructive conflicts have erupted over the identity of the property conserved and the conditions of its conservation.

The first of these conflicts, fought out in the early eighteenth century, concerned the "force" of a particle or set of particles. "Force" could mean a particle's mass m multiplied by its velocity v (momentum), mv^2, or $mv^2/2$ (vis viva). Colin Maclaurin, Gottfried Leibniz, and Johann Bernoulli I put forward conflicting claims for the conservation of "force" based in metaphysical principles logically developed and eventually expressed mathematically. Experimental data was incorporated into various metaphysical schemes. These arguments intensified with the 1724 prize competition of



Discovery photograph of the positron, which revealed itself by the curvature of its track on either side of the lead plate in the middle of the cloud chamber. The photo was taken by Carl David Anderson (1905–1991) at Caltech in 1932.

the Paris Royal Academy of Sciences. Other laws and controversies followed including conservation of angular momentum (Jean d'Alembert, 1749). These quarrels died with their adherents after d'Alembert rooted rational mechanics in virtual velocity rather than conservation. The physical conditions governing momentum, vis viva, energy, force, and so on were disentangled only in the nineteenth century.

Another conserved quantity of the eighteenth century was weight, which became an important guide to chemical theory with the discovery and identification of the several sorts of air. Conservation of weight became a foundation of the reformed chemistry of Antoine-Laurent Lavoisier. A third conservation law developed during the eighteenth century had to do with static electricity. Benjamin Franklin's theory of positive and negative electricity (1747) explicitly conserved charge and, moreover, made good use of the law in explaining the operation of the Leyden jar. Later natural philosophers, who used two electrical fluids where Franklin had made do with one, also practiced, if they did not make explicit, the conservation of electricity. Most theories of caloric, the weightless matter supposed to cause the phenomena of heat also supposed its conservation. Conservation laws in physical sciences were thus well established by 1800.

During the nineteenth century, conservation became a tool for discovery. In 1824, the military engineer Sadi Carnot (1824) applied the principle of conservation to caloric considered as the fuel of steam engines. The work extracted from the engine came from the cooling of the caloric from the temperature of the boiler to that of the environment just as the fall of water works a mill. Carnot's analysis, which resulted in the important insight that no engine more efficient than a reversible one can exist, was put into mathematical form by Benoit-Pierre-Émile Clapeyron in 1837 and largely ignored. Meanwhile, Michael Faraday, William Grove, and others explored the conservation of force, including electricity and magnetism.

In the 1840s, this work changed direction and several men from various backgrounds became "discoverers" of the conservation of energy. William Thomson, Lord Kelvin, developed Clapeyron's work, which led him to the definition of absolute temperature. In 1847 Thomson heard James Joule present an account of his measurements of the heat produced by an electrical current (Joule's law) and by mechanical motion. Joule had concluded that the forces of nature were not conserved but transformable one into another in accordance with an exact calculus. A certain amount of heat will always generate the same amount of mechanical work (mechanical equivalent of heat).

In *The Conservation of Force* (1847), Hermann von Helmholtz announced a general principle of nature that he extracted from a representation of matter as a collection of atoms held together by central forces. He equated the change in vis viva of a particle moving under the influence of a center of force to the change in the "intensity of the force." He identified the latter with the potential function introduced earlier by Carl Friedrich Gauss. Helmholtz showed how the results of experiments, like Joule's measurements of the production of heat in current-carrying wires, supported his principle of the interconvertibility of force.

In 1850, Rudolf Clausius put forward the clearest statement of the conservation of energy. He redid Carnot's analysis, replacing the conservation of caloric by the conservation of the "energy" of the perfect gas he assumed as the working substance of his heat engine and gave a mathematical expression for the conservation of energy, the first law of thermodynamics. Later he presented heat as the vis viva of gas molecules and the raising of a weight by the engine as the transformation of one type of mechanical energy (kinetic) into another (potential). In the second half of the nineteenth century, the conservation of energy became a mainstay of the physical sciences.

The conservation of energy had no prominent place in James Clerk Maxwell's kinetic theory or statistical mechanics but was central to Ludwig Boltzmann's work on both mechanics and thermodynamics. J. Willard Gibbs extended thermodynamics from physics into chemistry and developed, along with Helmholtz, other conservation laws (enthalpy and free energy) useful in physical chemistry. Energy conservation underwrote a new philosophical approach to physics, developed by Wilhelm Ostwald and Georg Helm. Also, Maxwell reworked his theory of electromagnetism and light within an energy framework using Thomson and Peter Guthrie Tait's *A Treatise on Natural Philosophy* (1867) as a guide.

Despite these substantial acquisitions, physicists had trouble making energy conservation fit certain phenomena of heat and radiation, and its applicability to radioactivity at first appeared doubtful. The bleak situation, which Thomson described as clouds over the otherwise sunny landscape of physics, was saved by the quantum theory of Max Planck and the demonstration of the conservation of weight and energy in radioactive decay through measurements by Marie Sklodowska Curie, Ernest Rutherford, and others and the mass-energy law ($E = mc^2$) of relativity.

Conservation of energy was an integral part of Niels Bohr's theory of atomic structure (1913). As the problems of his quantized atoms mounted in the early 1920s, however, he limited conservation of energy to the average of all the interactions of atoms with the electromagnetic field, and freed individual interactions from the necessity of obeying the first law of thermodynamics (1924). This *lèse majesté* played a part in Werner Heisenberg's quantum mechanics (1925), which changed the place of conservation laws in physics. Conservation laws now sprang from the mathematical symmetries inherent in the expressions for the matrices representing the operations that take a physical system from one state to another. Symmetry here required that under geometrical change or time reversal the mathematical form remains the same: a rotation in space implied conservation of angular momentum; time reversal, conservation of energy; and linear translation, conservation of momentum. In addition, there was a nonclassical symmetry associated with the intrinsic angular momentum (the spin) of a particle at rest. In the 1930s, an associated concept, isospin, was introduced and developed into a method of classifying the known nuclear particles. During the 1950s, isospin helped in classifying and predicting antiparticles and in generating a new conservation law, the conservation of nucleons.

To explore the nucleus physicists had to incorporate light into their theories of the atom and nucleus. The simplest problem, the interaction of the electron and the electromagnetic field, included a synthesis of quantum mechanics and the special theory of relativity. Techniques developed to bring convergence (renormalization) often forced changes in the conception of the nucleus and its constituents. P. A. M. Dirac's derivation of the wave equation for the electron (1928) implied the existence of negative energy states, which he interpreted as the domain of an "antiparticle" with the same mass as the electron but with positive charge. In Dirac's theory the two sorts of electrons could be created and annihilated together and contradicted an implicit assumption in quantum mechanics—the conservation of particles. Dirac's interpretation gained credence through Carl David A. Anderson's observation in 1931 of the positron (positive electron) in tracks made in his cloud chamber by cosmic rays.

The problem of beta decay further undermined assumptions as basic as the conservation of energy and momentum. Wolfgang Pauli suggested in 1931–1932 that an undetected particle of zero mass and electrical charge, named the neutrino by Enrico Fermi, carried away the missing energy and momentum. The neutrino first revealed itself directly in experiments done by Frederick Reines and Clyde L. Cowan in 1956.

The development of particle accelerators resulted in the discovery or manufacture of more and more "fundamental" particles and graver and graver problems for conservationists. Novelties included particles produced in associated pairs under circumstances so improbable that physicists gave them a quantum number named strangeness. Scientists postulated a new force within the nucleus, the weak force. The neutrino became a left-handed particle and the antineutrino right-handed. Conservation laws again needed revision, including those springing from the assumption of parity (P) conservation in weak interactions. (Parity requires that a device and its mirror image, if made of the same materials, function in the same way.) Nonconservation of parity led to investigations of other symmetry relations and their conservation laws, including charge conjugation (C), in which all the charges entering an equation become their opposites, and time reversal (T), in which the time variable t is changed to $-t$. The strongest result that physicists could produce was the conservation of CPT, in which the transformations C, P, and T simultaneously take place, with the corollary that if T conserves the relations, so does CP.

Experiments to test nonconservation under P demonstrated that some particles are intrinsically right-, and others intrinsically left-handed. By the 1970s a generally accepted model for particle behavior emerged, the so-called Standard Model, whose fundamental building blocks, the quarks, have fractional charges 1/3, 2/3, −1/3 of the electron's. In this model, however, all hadrons (protons, neutrons, etc.) should have the same mass, which they do not. The theory "breaks" this unwanted symmetry by introducing different sorts or "flavors" of quarks. Further symmetries and conservation laws emerged from the requirement that quarks be confined by the strong force. This led to further symmetries and new conservation laws. The dependence of physical interpretation on difficult mathematics seemed justified by the experimental identification of the different quarks in the 1970s and 1980s.

Thus conservation laws, at first intuitive expressions of physical regularities and lately of esoteric mathematical symmetries, have guided physics over the past 250 years.

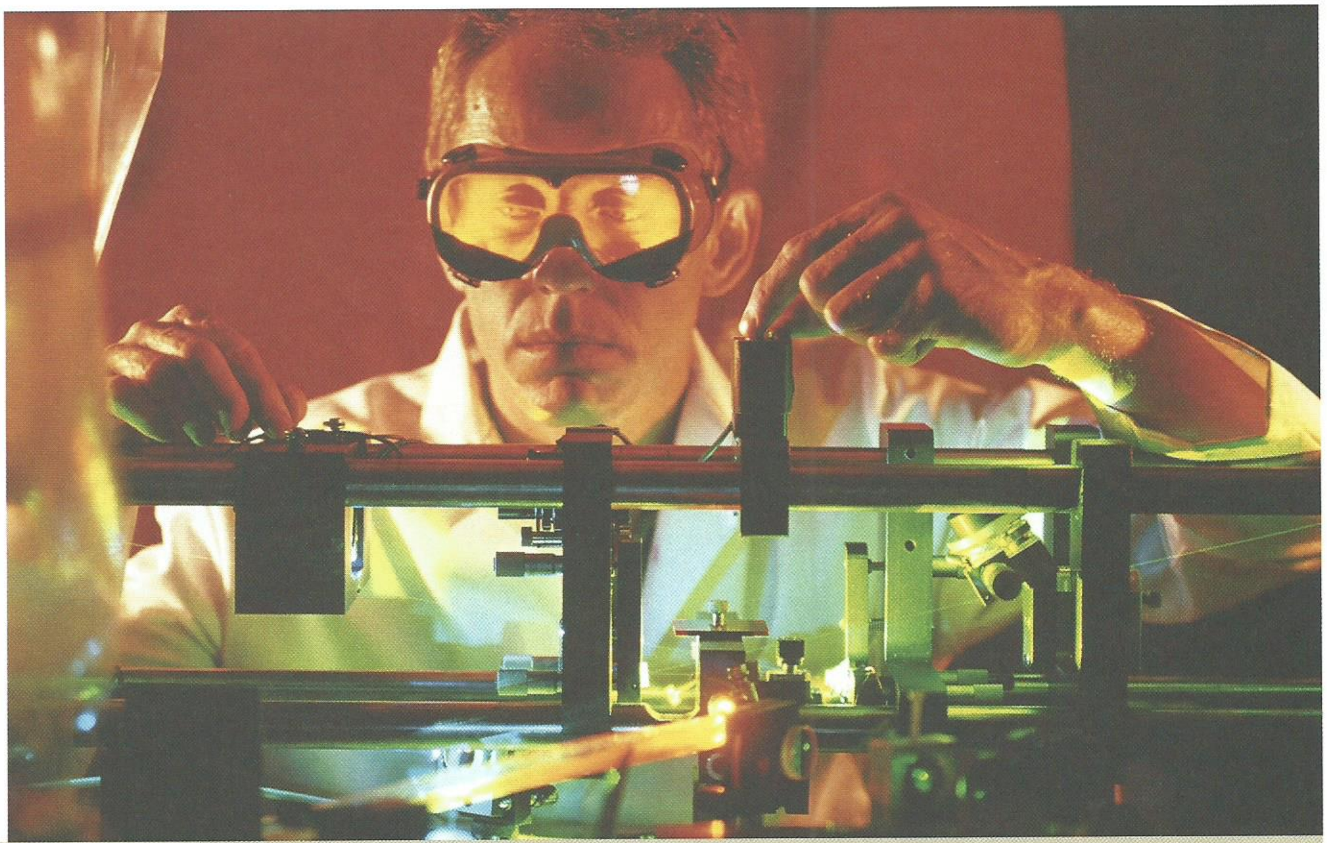
Elizabeth Garber

CONSTANTS, FUNDAMENTAL. The belief that numbers constitute the essence of the universe runs deep in the human experience. The patterns of the sky and seasons provided the first opportunity for discovering nature's numbers, and the agricultural, commercial, and religious needs of early civilizations provided the motivation for inscribing them in calendars. The Greeks in particular anchored thought in number, both in the metaphorical, as in the speculations of the Pythagoreans and the Platonists, and in the practical, as in the exact geometrical astronomy of Hipparchus and Ptolemy. These two approaches came together from time to time, notably in the work of Johannes Kepler, who combined numerological beliefs in the literal harmonies of the celestial spheres with Tycho Brahe's precision measurements to discover that the cube of a planet's average orbital diameter divided by the square of its orbital period was the same value, no matter the planet.

Galileo Galilei confined his numerical endeavors to terrestrial bodies. He measured the rate of fall of various weights and found that the ratio of the distance traveled and the time of fall squared was the same for each body examined. Galileo's falling bodies and Kepler's fruitful numerology came together in Isaac Newton's theory of universal gravitation. Newton's theory implied the existence of a fundamental constant (later labeled G) that specified the force of attraction not only between a planet and the Sun but also between a falling object and Earth.

Not much attention was paid to these constants of gravity. The mathematical methods of the time, which focused on the form of ratios between quantities and not their proportionality constants, veiled the importance of the constants themselves. Even in the late eighteenth century, Henry Cavendish devised his famous torsion balance experiment not to measure the force between two weights and thus what modern physicists call the gravitational constant, but to measure the density of the earth. A significant exception to the lack of interest in the natural constants prevalent in early modern science was the measurement of the speed of light by Ole Rømer in 1675. A possible explanation of this exception is that, in contrast to gravitational acceleration, speed was conceptually familiar and, in the case of light, would be determined by astronomical phenomena—Rømer used eclipses of Jupiter's satellites—frequently subjected to measurement.

Not until the middle of the nineteenth century did the modern interest in fundamental constants in physics evolve. A broad-based quantifying spirit that had arisen during the eighteenth century supplied the general motivation, and the burgeoning telegraph industry, in dire need of well-defined electrical units and standards, supplied the immediate requirement. In 1851, Wilhelm Weber proposed a system of electrical units founded on the metric system. A decade lat-



Researcher using a tabletop dye laser to drive an atomic clock. Very exact measurement of time figures are used in the determination of fundamental constants.

er, the British Association for the Advancement of Science, under the leadership of William Thomson, Lord Kelvin and James Clerk Maxwell, took up the challenge of promulgating an international system of electrical units and standards that could meet the needs of both science and industry. In such a system, certain fundamental quantities of nature played a key role, such as the magnetic permeability and electrical permittivity of the ether. The work also raised the possibility of defining a "natural," non-arbitrary system of units, perhaps based on the wavelength, mass, and period of vibration of the hypothesized atoms.

Meanwhile, certain key numbers were appearing in path-breaking physical theories. James Joule demonstrated the mechanical equivalent of heat and calculated its value. Ludwig Boltzmann reframed thermodynamics in terms of statistics and an important constant, later called *k,* relating a molecule's average energy to temperature. Max Planck introduced another key constant related to molecular energy, *h,* in his blackbody radiation law. Maxwell's electromagnetic theory emphasized that the speed of light *c* was actually the speed of electromagnetic radiation in general. Albert Einstein's theory of special relativity and his mass-energy equivalence, $E = mc^2$, further established the fundamental status of *c.* And Joseph John Thomson's discovery of the electron introduced its mass and charge (m_e and e) as candidates for the fundamental quantities of matter and electricity.

As the recognized physical constants multiplied into the twentieth century, they raised the question, how fundamental? Although they could be categorized by type, such as properties of objects or factors in physical laws, and some clearly possessed deeper and broader significance than others, it became apparent that many of them were interrelated and that the term "fundamental" always hid some arbitrariness.

A second question was, how precise? The 1920s and 1930s saw an informal international effort to identify not only the best extant value of each fundamental constant but also its precision. The technologies of World War II, and offspring like the laser and atomic clock, assisted by enabling revolutionary increases in decimal places. In the 1960s the project gained a formal footing with the establishment by the International Council of Science of a Committee on Data for Science and Technology (CODATA) and its Task Force on Fundamental Constants. It surveyed the literature and produced a set of "best" values for fundamental constants in 1973, 1986, and 1998.

The hard-eyed quest for the next decimal place did not eradicate interest in numerology, however. Certain combinations of *e, h,* and *c* seemed to contain deeper magic. The dimension-less constant e^2/hc, for example, was revealed by quantum electrodynamics to be the constant that defined the strength of the electromagnetic force. Dimensionless constants held great allure because their value did not depend on the system of units chosen, but seemed to be pure numbers of the universe. Moreover, some simple combinations of fundamental constants yielded very large dimensionless numbers all on the order of 10^{40}. In his "large number hypothesis," P. A. M. Dirac proposed that this coincidence hinted at an undiscovered law of the universe. The large number hypothesis also raised the question, how constant?, as it implied that some fundamental constants, such as G, might vary as the universe evolves. On some cosmological theories, small changes in the values of the constants can trigger large consequences for the development of the universe. Only for values close to those observed could complex life develop. Thus a consideration of the fundamental constants renewed interest in the anthropic principle and raised hopes that nature's numbers could be derived from the fact of human existence.

LARRY R. LAGERSTROM

COSMIC RAYS. The first explorers of radio-activity found it in air and water as well as in the earth. Shielded electroscopes placed out of doors lost their charges as if they were exposed to penetrating radiation. Since leak diminished with height, physicists assigned its cause to rays emanating from the earth. As they mounted ever higher, however, from church steeples to the Eiffel Tower to manned balloons, the leak leveled off or even increased. In 1912–1913, Victor Hess of the Radium Institute of Vienna ascertained that the ionization causing the leak declined during the first 1,000 m (3,280 ft) of ascent, but then began to rise, to reach double that at the earth's surface at 5,000 m (16,400 ft). Hess found further, by flying his balloon at night and during a solar eclipse, that the ionizing radiation did not come from the sun. He made the good guess—it brought him the Nobel Prize in physics in 1936—that the radiation came from the great beyond.

The need to know the meteorological state of the upper atmosphere for directing artillery during the Great War improved balloon technology. Robert Millikan, who would receive the Nobel Prize in 1923 for his measurement of the charge on the electron, was a powerful organizer of American science for war. His observations made with Army balloons seemed to show that the ionization in the atmosphere declines continually from the earth's surface. Experiments in lakes at different heights showed him his error and he became the champion of what he called "cosmic rays." He regarded them as the "birth cries of infant atoms" since, by his calculations, the relativistic conversion of mass into energy during the formation of light elements from hydrogen would produce high-frequency radiation (photons) of the penetrating power of Hess's rays.

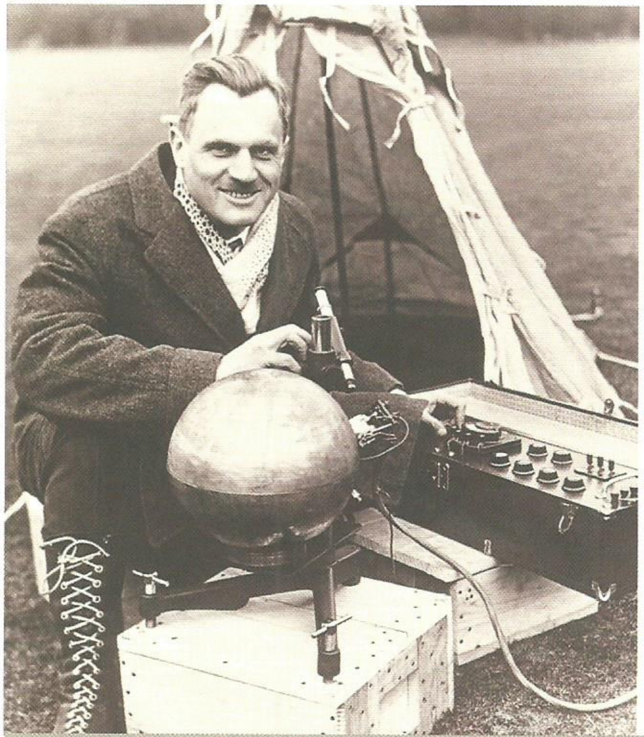
The advance of electronics transformed the study of cosmic rays from a guessing game to an exact, expensive, and productive science. In 1929, Werner Kolhörster, who had confirmed Hess's measurements, and Walther Bothe placed two Geiger counters one above the other, separated them by a lead block, and arranged a circuit to register only when both counters fired simultaneously. They detected too many coincidences for photons to produce and they inferred that cosmic-ray primaries must be charged particles with at least a thousand times more energy than the hardest rays from radioactive substances. After learning the coincidence method from Bothe (who received a Nobel Prize for it in 1954), Bruno Rossi, one of the Italian pioneers in the field, set three counters in a triangular array and deduced the existence of showers of particles produced by stopping the primaries (1932). A new particle, the positive electron (positron), was found among the secondaries in cloud chambers by Carl David Anderson, who worked with Millikan at the California Institute of Technology (Caltech), and by P. M. S. Blackett and Giuseppe P. S. Occhialini, who used Rossi's electronics. Anderson and Blackett received Nobel Prizes in 1936 (sharing with Hess) and in 1948, respectively.

Cosmic rays became big science when Arthur Holly Compton (Nobel Prize, 1927) undertook to annihilate Millikan's primary photons. Compton designed a method to show that the sea-level intensity of cosmic rays at the poles exceeds that at the equator. If the primaries were charged particles, they would be deflected by the earth's magnetic field more strongly the lower the magnetic latitude. Compton's project mobilized sixty investigators who carried expensive standardized apparatus on eight expeditions. Government agencies used to funding geophysical work and the Carnegie Institution of Washington paid the bills. By 1934 Compton's company had confirmed the latitude effect and silenced the birth cries of infant atoms.

The victory at first appeared to have a heavy cost, however, since quantum electrodynamics required that the charged primaries, if electrons or protons, be absorbed more quickly by the atmosphere than was compatible with their intensity at the surface. Anderson's cloud chamber soon disclosed the existence of a secondary particle (now called the μ meson or muon) whose intervention would slow the absorption of cosmic rays. At first identified with the particle Hideki Yukawa (Nobel Prize,1949) had postulated as the carrier of nuclear force (now called the π meson or pion), the muon has played an important role in the systematics of the standard model. It also afforded, through the difference in time between its decay in flight and at rest, the first experimental confirmation of the time dilation required by the theory of relativity.

The last major contributions of students of cosmic rays to fundamental physics occurred just after World War II. With the help of photographic emulsions developed for wartime use, Cecil Powell (Nobel Prize, 1950) and his colleagues at the University of Bristol (including Cesar Lattes) caught a pion as it turned into a muon, confirming the growing realization that Anderson's meson was not Yukawa's. In the same year, 1947, two other British physicists, George D. Rochester and Clifford C. Butler, found evidence in cloud chamber tracks of the decay of unknown neutral particles (now called hyperons) into neutrons, protons, and pions. Two years later, Powell, immersed again in emulsions, found a particle (the K meson) that decayed into three mesons.

The data needed to unravel the relations among elementary particles did not come from cosmic rays, however, but



Arthur Compton (1892–1962), US physicist, who won the Nobel Prize in physics in 1927 for showing that high-energy photons behave like particles in collisions with electrons. Here he is shown some years later in the field chasing cosmic rays.

from accelerators. Already in 1947 the Berkeley synchrotron was making μ and π mesons in greater quantity than cosmic rays furnished. Whereas the synchrotron confirmed and extended the discoveries of mesons made through the study of cosmic rays, cosmic-ray physicists could find the antiproton only by scanning emulsions exposed to the beam of the Berkeley Bevatron, where it was first made and detected in 1955. In compensation, cosmic-ray physicists came to agree that the primary radiation striking the atmosphere consists almost entirely of protons, a substantial sprinkling of alpha particles and other nuclei, and a few electrons.

The invention of artificial satellites gave cosmic-ray physicists a needed fillip. *Sputnik I* and the U.S. runners-up, *Explorer I* and *Explorer III,* all carried counters to measure cosmic-ray intensity. The *Explorers'* counters stopped working high above the earth. The man in charge of the instrumentation, James A. Van Allen of the University of Iowa, interpreted the silence as evidence that the satellite had passed through a region so full of charged particles that the counters jammed. The region, now known as the Van Allen Belt(s), consists of cosmic-ray and solar particles trapped in the earth's magnetic field. Hess's assertion that the Sun does not contribute to cosmic radiation succumbed to technological advances that replaced the balloons of the years around World War I with the rockets of the Sputnik era.

J. L. HEILBRON

COURTS AND SALONS. Since the middle ages, European princely courts were populated by practitioners of natural philosophy, mostly physicians and astrologers catering directly to the sovereign's body and peace of mind. Their number increased in the early modern period as courts became larger and wealthier, and their activities diversified. Natural history, alchemy, natural magic, clocks, automata, lodestones, anamorphic devices, mirrors, telescopes, microscopes, and, eventually, experiments took their places at court.

These subjects did not share the same courtly spaces or visibility. Some were incorporated in court pageants, played out in court disputations, or displayed in botanical gardens, cabinets of curiosity and, later, galleries and museums. Others were confined to the prince's study or to the workshops of court jewelers, glassmakers, or apothecaries. Princes and courtiers had an eye for intriguing objects and intriguing philosophers. They did not care where the objects fell in classifications of knowledge or academic disciplines. As shown by the remarkable variety of objects included in early modern aristocratic cabinets of curiosity, the line between *naturalia* (natural objects) and *mirabilia* (spectacular human artifacts) often blurred. Similarly, the courtly interest in artistic representations of botanical and zoological specimens was rooted in their location at the intersection of natural history and the visual arts.

Spectacle was serious business at court. The power of the prince and the relative positions of his aristocratic subjects were continuously staged through a multitude of rituals, some of them quite spectacular. Natural philosophy moved from serving the prince's personal and bodily needs to strengthening and legitimizing his political role and authority through the production of novelties and curiosities—objects that would help to cast him as a unique person entitled to a unique, exalted political role. The personal demeanor and the writing and argumentative style of the natural philosopher also adapted to fit courtly standards of elegance, wit, and nonchalance.

The court employed natural philosophers, paid them well, and, most importantly, provided them with a social status they could attain nowhere else. The implications of a court position extended well beyond material rewards or personal status to the authority of the natural philosopher and his discipline. Disciplinary hierarchies (quite rigid in the university and the craft guilds) could be easily redrawn if the prince wished it so. Artisans could become artists and (here Galileo is the exemplar) mathematicians could become philosophers.

On the other hand, court life demanded a certain level of social and linguistic skill and only topics that were novel, spectacular, and nontechnical were likely to be approved. Moreover, the court favored objects, not theories or long-term projects. Although princes appreciated and often promoted philosophical disputations, they worried more about the quality of the performance than the truth-value of the debate. Ultimately, natural philosophers at court, being courtiers, existed at the whim of the prince. Reaction to these disadvantages of the court system was a central impetus in the establishment of scientific academies—institutions often connected to courts but with relative stability and some tools for self-governance.

Salons were gatherings in the urban homes of nobles or patricians. Their size, schedule, discussion topics, exclusivity, or internal structure varied greatly, as did the role of women in them. Usually organized and managed directly by the host, they relied in some cases on a litterateur or philosopher (the "secretary") to run the salon's activities. As an institution, the salon resembled both the court and the academy. In mid-seventeenth-century Paris, some salons amounted to small full-fledged courts; others were the direct ancestors of royal academies of science. In turn, in the eighteenth century many provincial academies resembled seventeenth-century urban salons in the scope of their interests and the nature of their membership.

Like courts, salons played an important role in the development of the scientific community and, more generally, the so-called republic of letters. They provided forums for discussion of the members' work or, more often, of philosophical literature and news. Their polite conversation helped to prepare non-noble savants for careers at court or in academies. But conversation could turn contentious, disrupting the sociability that underpinned the salons, and cast them as places where natural philosophy was consumed, not produced.

The salons supported and constrained natural philosophy the way the court did. The court could be more effective in providing social legitimation and financial support. The salons offered social training, more leeway in discussion topics, somewhat greater accessibility, and contacts that might make a career—Bernard de Fontenelle and Jean d'Alembert's careers were made in this way. Unlike the court, the salon came with schedules for meetings and activities but, like the court, might come to an end with the death of its patron. Also like courts, salons tended to blend natural philosophical interests with literature, poetry, and moral questions.

Salons have been celebrated as hotbeds of Enlightenment thought and as crucial sites for women natural philosophers—an association that can be traced back to the seventeenth century. But even as they reached an apex of cultural prominence, salons came to be associated with scientific marginality. By the eighteenth century, academies had taken over as the main scientific institutions, relegating the salons to the role of launching pads for future academicians or merely occasions for the nonprofessional consumption of academic science.

Mario Biagioli

CREATIONISM is a popular movement arising from deep-seated objections to perceived religious and social consequences of the acceptance of evolution and from the conviction that evolution has never been satisfactorily demonstrated. These objections predate Charles Darwin. "If the book be true," Cambridge geologist Adam Sedgwick wrote of the evolutionary speculations published (anonymously) by Robert Chambers in *Vestiges of the Natural History of Creation* (1844), then "the labours of sober induction are in vain; religion is a lie; human law is a mass of folly, and a base injustice; morality is moonshine; our labours for the black people of Africa were works of madmen; and man and woman are only better beasts."

Modern creationists raise similar concerns, linking evolution with racism, sexual promiscuity, totalitarianism, nihilism, and various forms of irreligion. Many philosophical and empirical objections to evolution voiced today—the existence of significant "gaps" in the fossil record (which Darwin admitted and modern paleontologists continue to debate), questions about the limits of variability in organisms, the difficulty of explaining the origin of complex organs such as the eye (also admitted by Darwin), and the denial that the earth has existed long enough for natural selection to produce all forms of life—were likewise expressed in the mid-nineteenth century, for example in the review of the fourth edition of Darwin's *On the Origin of Species* by Scottish engineer Fleeming Jenkin (*North British Review*, 1867). Political and social objections—including the argument (detailed by biologist Vernon Lyman Kellogg in *Headquarters Nights* [1917]) that there were close links between the teaching of evolution and German militarism—drove prominent American politician and lawyer William Jennings Bryan to head efforts to outlaw the teaching of evolution in publicly funded American schools, culminating in the staged trial of John Scopes in Dayton, Tennessee (1925).

Although modern creationists still try sometimes to prevent the teaching of evolution, more often they push for "equal time" to teach their ideas alongside evolution in public schools. They challenge the ways in which evolution is presented in standard textbooks, calling for more attention to its perceived difficulties and clearer statements about the nature of evolution as a "theory" rather than a fact. Creationists have also developed their own alternative textbooks; most are written for fundamentalist religious schools though some are intended for public schools, which do not use them, as a rule.

Where most earlier antievolutionists, including Bryan, accepted evidence for an old earth and universe and did not see the biblical flood as a major geological event, the self-styled "scientific creationists" of today insist on a young earth (roughly the traditional biblical age of six thousand years) and embrace "flood geology," the claim that most fossiliferous rocks are relics of the flood and therefore not evidence for evolution. These ideas are central to *The Genesis Flood* (1961) by engineer Henry Morris and theologian John C. Whitcomb, Jr., the single most important creationist book since the 1920s. This work, which popularized flood geology for a wide audience of conservative Protestants, rests on an idea that had circulated for many years within the thoroughly creationist Seventh-day Adventist religious tradition—an idea ultimately derived from prophetess Ellen Gould White but directly taken from Canadian schoolteacher George McCready Price, author of *The New Geology* (1923) and many other works. Morris helped found two organizations, the Creation Research Society and the Institute for Creation Research (San Diego), that are leading disseminators of creationism. Their reach extends beyond the United States to a number of other countries, though creationism—as has been true for most of its history—remains largely an American phenomenon.

Edward B. Davis

CRYSTALLOGRAPHY. Crystals have attracted attention because of their striking and often beautiful forms since early in human history. As an object of systematic study, they have attracted the attention of very different investigators: natural philosophers, mineralogists, chemists, physicists, mathematicians, metallurgists, and biologists. Only in the twentieth century did crystallography become an institutionalized scientific discipline. Perhaps for this reason a comprehensive history of the study of crystals is yet to be written.

In the sixteenth and seventeenth centuries, natural historians thought that crystals, like snowflakes and fossils, bridged the conventional categories of the material world. Like living things, their symmetric form indicated organization. It was even possible to see them growing. Yet they did not seem to be fully alive. Some observers speculated that the variety of crystalline appearance indicated astrological influence, others that it evidenced nature's ability to impose form on matter. Crystals were thought by some to grow from seeds in the earth; by others, from circulating fluids. Mechanical philosophers such as Robert Boyle and Robert Hooke saw in the regular form of crystals a reflection of the underlying arrangement of corpuscles or atoms. Nicolaus Steno, in his *Produmus to a Dissertation on Solids Naturally*

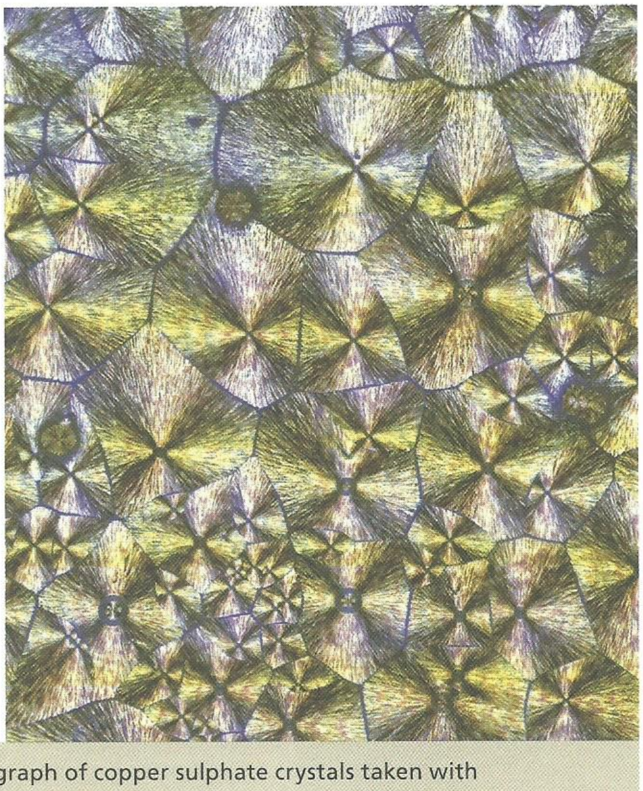
Clarence Darrow, lawyer for the defense of John T. Scopes, tried for teaching evolution in the public schools, and William Jennings Bryan, lawyer for the prosecution, during a lull in the proceedings at Dayton, Tenessee, in 1925

Contained within Solids (1669), explored possible manners of growth and stated the principle that crystals of the same kind have the same angles between adjacent faces.

In the eighteenth century, the study of crystals advanced on a number of fronts. Carl Linnaeus proposed that minerals could be classified by counting their faces, a suggestion of limited utility at the time since most minerals do not appear crystalline to the naked eye and since the polarizing microscope was yet to be invented. René-Just Haüy, professor of mineralogy at the Muséum d'Histoire Natural in Paris, followed earlier work by Romé de l'Isle on the relation of visible crystal forms to the units composing them. In his *Traité de cristallographie* (1822), Haüy suggested that cleaving a crystal divided it into one of six basic polyhedral units, themselves formed of smaller units that might or might not have other polyhedral forms. William Wollaston's invention of a reflecting goniometer that used light rays to measure crystal angles made possible much more precise measurements of crystal forms.

Haüy assumed a univocal relation between crystal form and chemical composition. The chemist Eilhard Mitscherlich dissented. He observed that substances with different chemical compositions could crystallize in the same form, a property he called isomorphism. This bothered the young Louis Pasteur who took advantage of the peculiar optical properties of crystals to investigate the matter further. He carefully separated tartrate crystals that differed just slightly in their facial angles. Polarized light passed through a solution of one set of crystals rotated in one direction; when passed through a solution of a second set, in the reverse—indicating, Pasteur argued, crystalline asymmetry at the molecular level.

The optical properties of minerals proved a reliable aid in identifying them. Henry Clifton Sorby's polarizing microscope enabled mineralogists to examine rocks in thin section and identify their previously invisible crystal constituents. This became a basic technique of petrography. In the second half of the nineteenth century, physicists studied the elasticity, density, and electrical properties of minerals. In 1880, Pierre Curie and his brother Jacques-Paul discovered that pressure exerted at the right point on a crystal produced an electric field, a phenomenon known as piezoelectricity. Pierre later incorporated this effect in an electrometer used in the detection of radioactivity. Other scientists worked out the mathematical possibilities for crystal structure: Auguste Bravais, professor of physics at the École Polytechnique of Paris, showed in his *Études cristallographiques* (1866) that only fourteen possible arrangements of points in space lattices were possible.



Micrograph of copper sulphate crystals taken with polarized light; the crystals appear as a bright, intense blue to the naked eye.

The discovery of X rays revolutionized crystallography. In 1912, Max von Laue and his group at the University of Munich photographed the diffraction pattern produced by a copper sulphate crystal, showed that X rays passed through a crystal scattered and deflected at regular angles. William Henry Bragg, professor of physics at the University of Leeds, and his son William Lawrence Bragg, then a student at Cambridge, realized that the pattern depended on the atomic structure of the crystal and succeeded in analyzing the crystal structure of the mineral halite (sodium chloride). This in turn led to the invention of the X-ray powder diffractometer. X-ray crystallographers began organizing themselves into formal bodies shortly after World War I. In 1925, they held an informal meeting in Germany to restore disrupted relations. At the Royal Institution in London and the University of Manchester, the Braggs trained students from all over the world in the techniques of X-ray crystallography. Societies were founded in Germany in 1929, the United States in 1941, and the United Kingdom in 1943.

Zeitschrift für Kristallographie became the leading journal in the field in 1927 when it started accepting papers in French and English as well as in German. International cooperation in crystallography revived immediately after World War II. The International Union of Crystallography was founded and quickly joined the International Council of Scientific Unions, the intermediary for UNESCO funding. Soon after came the debut of *Acta crystallographica*, quickly to become the premier journal in the field. X-ray crystallography proved crucial to the rapidly expanding field of molecular biology, itself the result of the coalescence of biochemistry and crystal structure analysis. After the discovery that proteins could be crystallized, W. T. Astbury began exploring their structure with X rays. In the late 1950s, the double-helix structure of nucleic acid, predicted by Francis Crick and James D. Watson, was confirmed by Maurice Wilkins and Rosalind Franklin; in the same period Max Perutz and John Kendrew determined the structure of hemoglobin and myoglobin.

In the 1960s, X-ray crystallographers began adding computers to their apparatus, increasing the speed and precision of analysis. X-ray crystallography remains the most powerful, accurate tool for determining the structure of single crystals. It is widely used in disparate fields including mineralogy, metallurgy, and biology.

RACHEL LAUDAN

CYBERNETICS is the discipline that studies communication and control in living beings and machines or the art of managing and directing highly complex systems. Concepts investigated by cyberneticists include systems (animal or machine), communication between systems, and their regulation or self-regulation.

The MIT mathematician Norbert Wiener invented the term in 1947 (first used in print, 1948) from a Greek term for "steersman" or "governor." The origins of cybernetics lie in the development of feedback mechanisms such as the spring governors for steam engines invented by James Watt and Matthew Boulton (1788), James Clerk Maxwell's consideration of ships' steering engines (1868), and Weiner's involvement in developing automated range finders (1941), which led to the construction of the ILLIAC computer.

Wiener joined MIT in 1919 as a professor of mathematics. Together with MIT neurophysiologist Arturo Rosenblueth he established small interdisciplinary teams to investigate unexplored links between established sciences. Working with the engineer Julian Bigelow, Wiener developed automatic range finders for antiaircraft guns able to predict an aircraft's course by taking into account the elements of past trajectories. Wiener and Bigelow observed the seemingly "intelligent" behavior of these machines and the "diseases" that could affect them. The servomechanisms appeared to exhibit "intelligent" behavior because they dealt with "experience" (recording of past events) and predictions of the future. They also observed a strange defect in performance. With too little friction, the system entered a series of uncontrollable oscillations. Rosenblueth pointed out that humans exhibited similar behavior and Wiener inferred that in order to control a finalized action (an action with a purpose) the circulation of information needed for control must form a closed loop, allowing the evaluation of the effects of previous actions and the adaptation of future conduct based on them. Wiener and Bigelow thus discovered the negative feedback loop.

Rosenblueth's multidisciplinary teams approached the study of living organisms from the viewpoint of a servomechanism engineer and considered servomechanisms from the perspective of the physiologist. Rosenblueth and neurophysiologist Warren McCulloch (then director of the Neuropsychiatric Institute at the University of Illinois) brought together mathematicians, physiologists, and mechanical and electrical engineers in 1942 at a seminar at Princeton's Institute for Advanced Study. After ten more meetings, two seminal publications resulted: Wiener's *Cybernetics, or Control and Communication in the Animal and the Machine* (1948) and Claude Shannon and Warren Weaver's *The Mathematical Theory of Communication* (also 1948), which established information theory. Although it had an interdisciplinary orientation, early cybernetic studies employed an engineering approach focusing on feedback loops and control systems and on constructing intelligent machines. Influenced by the changing and challenging perspectives, McCulloch moved from neurophysiology to mathematics and then to engineering.

The new disciplines inspired biologist Ludwig von Bertalanffy to found the Society for General Systems Research. The society included disciplines far removed from engineering: sociology, political science, and psychiatry. The excitement attracted researchers such as mathematician Anatole Rapoport, biologist W. Ross Ashby, bio-physicist Nicolas Rashevsky, economists Kenneth Boulding and Oskar Morgenstern, and anthropologist Margaret Mead. Mead urged Wiener to extend his ideas to society as a whole. The Society's *Yearbooks* first appeared in 1954 and exerted a profound influence on those interested in applying the cybernetic approach to social systems and to industrial problems.

Early interest in cybernetics in the USSR was stifled on ideological grounds but in 1955 Aleksandr Mikhailovich Lyapunov, founder of Soviet cybernetics and programming, along with Sergei Sobolev and Anatoly Kitov, published the first permitted paper on cybernetics in *Voprosy Filisofii* (Problems of Philosophy). Soon thereafter, V. M. Glushkov established the Institute of Cybernetics in the Ukraine though its independent work does not appear to have had much impact on western studies.

Cybernetics was closely related to the development of ENIAC (1946), EDVAC or EDSAC (1947), Whirlwind II (1951), and other early computers. The latter used a superfast magnetic memory invented by an electronics engineer from MIT's Lincoln Laboratory, Jay Forrester. Beginning in 1952, he coordinated the SAGE (Semi-Automatic Ground Environment) alert and defense system for the U.S. Air Force. It combined radar and computers for the first time to detect and prevent attacks by enemy rockets. Forrester designed SAGE to be capable of making vital decisions as information arrived while interacting in real time with humans inputting data and with other humans making decisions on appropriate reactions.

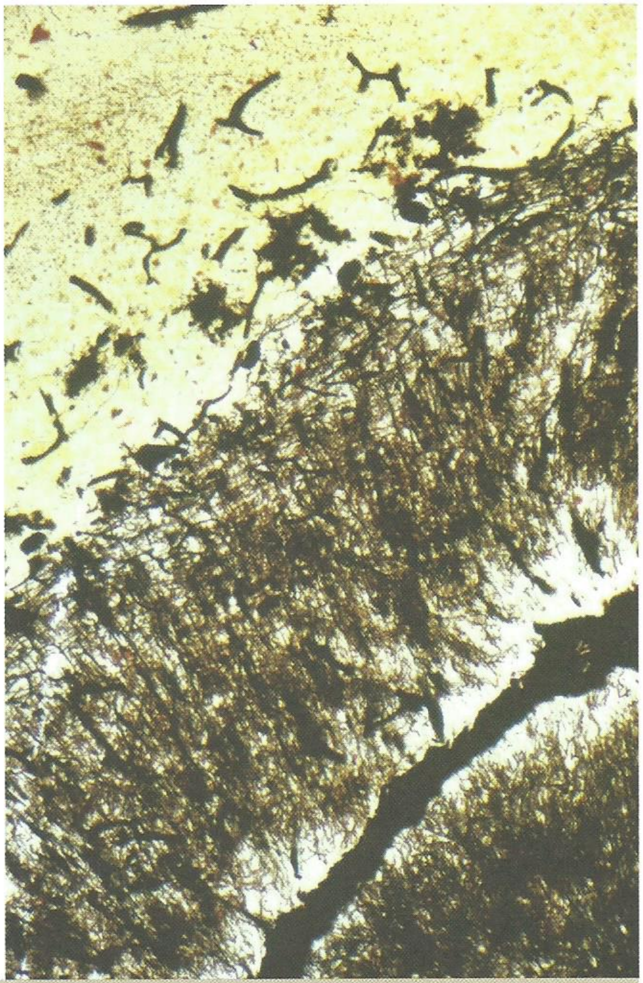
Ten years later, back at MIT, Forrester created industrial dynamics, which regards all industries as cybernetic systems in order to simulate and predict their behavior. In 1964, confronted with the problems of the growth and decay of cities, he extended industrial dynamics to urban systems (urban dynamics), generalized his theories as system dynamics, and published its definitive text, *World Dynamics* (1971).

Heinz von Foerster coined the term "second-order cybernetics" in 1970. First-order cybernetics concerned observed systems, and second-order cybernetics observing systems. Biologists like von Bertalanffy stayed at the first level. Second-order cybernetics deals with living systems and not with developing control systems for inanimate technological devices and explicitly includes the observer(s) in the systems under study. These living systems range from simple cells to human beings. From the 1970s, "cybernetics" has served as an umbrella term for several related disciplines: general systems theory, information theory, system dynamics, dynamic systems theory (including catastrophe theory), and chaos theory, among others. Cybernetics and systems science now constitute an academic domain encompassing recently developing "sciences of complexity," including artificial intelligence, neural networks, dynamical systems, chaos, and complex adaptive systems such as those used in flexible or multi-mirrored astronomical telescopes. Problems that appear beyond solution now may one day succumb to quantum computers able to mimic more closely the analytical powers of the human brain.

RANDALL C. BROOKS

CYTOLOGY. The term "cytology," denoting the study of plant and animal cells, has been in use from the 1880s, but it only acquired widespread currency in the early decades of the twentieth century. The seventeenth-century British natural philosopher and first Curator of the Royal Society of London, Robert Hooke, may, however, be regarded as the first cytologist. He observed, named, and figured vegetable cells using the recently invented compound microscope. Nehemiah Grew, using the same sort of microscope as Hooke, published many illustrations of vegetable cells. During the last quarter of the seventeenth century, the Dutch draper Antoni van Leeuwenhoek reported observations of structures including what would later be identified as protozoa and blood globules.

These were the efforts of a handful of individuals and did not amount to a concerted program of research into the min-



Purkinje cells in the human cerebellum, magnified 150 times

ute structure of living tissue. Only in the mid-nineteenth century did schools of histological inquiry began to develop. These histologists made use of new achromatic microscopes that corrected some of the optical defects of earlier microscopes. Among the most important figures in this first generation of microscopic anatomists were Jan Evangelista Purkyn, Professor of Physiology at Breslau, and Johannes Peter Müller, Professor of Physiology at Berlin. Müller in particular produced a school of microscopic observers who went on to produce important original research. One of these, Theodor Schwann, was to make a fundamental theoretical contribution to cytology.

In 1831, the Scottish botanist Robert Brown identified a nucleus in vegetable cells. Jacob Matthias Schleiden came to the conclusion in 1838 that cells were a ubiquitous feature of plant organization and that the nucleus played a crucial role in the growth of plant cells. When Schwann became acquainted with the results of Schleiden's researches, he recognized an analogy between these nucleated cells and certain structures he had himself discerned in animal tissue. In 1839, Schwann argued that the cell was the common unit of structure, function, and development in both plants and animals. This "cell theory" became a fundamental tenet of biology.

In 1846, Schleiden's former associate, Carl Wilhelm von Naegeli, concluded that in almost all cases new plant cells arose through the division of preexisting ones. Embryological studies made by Robert Remak supported the view that the same held for animal cells. The pathologist Rudolf Virchow was at first a proponent of free cell generation. By 1855, however, on the basis of his microscopic investigation into disease processes, Virchow rejected this concept of cytogenesis.

Later developments in cytology were closely associated with the increasingly refined techniques for fixing and staining tissue that became available to investigators. The German anatomist Walther Flemming elaborated techniques to reveal the internal structure of the cell. He was the first to describe the presence of thread-like bodies, later named chromosomes, in the nucleus, and to describe the role they played in cell division. Flemming coined the term "mitosis" for this process in 1879. In the 1890s, the mode of division characteristic of reproductive cells ("meiosis") was distinguished.

Oscar Hertwig had reported in 1876 that the fertilized ovum contained nuclear matter from both parents. Edouard van Beneden expanded upon these observations in 1883, giving a definitive account of the processes involved in the production of the new nucleus in the fertilized egg. The full significance of these cellular phenomena for the understanding of heredity came in the early twentieth century after the rediscovery of Gregor Mendel's ideas.

During this period cytology and genetics became increasingly intertwined. The work of the American biologist Edmund Beecher Wilson summed up what had been done in cytology in the previous half century and made a bridge to later developments: his *The Cell in Development and Inheritance* (1896) synthesized what was known about the structure and functions of the cell. In his later researches on the role of chromosomes in reproduction, he supplied the cytological basis for the researches of his associate, Thomas Hunt Morgan, on the mechanisms of heredity.

Although attention thus focused on the nucleus, the cell contents, or "cytoplasm," also received intensive study. Several observers discerned a reticular structure in the cytoplasm. By the end of the century, however, these appearances had been dismissed as artifacts produced by the fixatives employed. A considerable debate broke out during the mid-nineteenth century over whether the animal cell, like the vegetable, in all instances possessed a true "wall" or dividing membrane. Ernst Wilhelm von Brücke and Max Schultze argued against the traditional view of the cell as a bounded cavity. The essential parts of the cell were the nucleus and its surrounding "protoplasm."

Around the turn of the twentieth century, Carl Benda employed sophisticated staining methods to identify cytoplasmic inclusions to which he gave the name "mitochondria." Microscopy offered little insight into the functions these bodies might perform, although Benda speculated that they might play a role in heredity. Later biochemical analysis revealed that they participated in cell respiration. The structure of the mitochondria was elucidated after World War II by the use of the electron microscope.

In the second half of the twentieth century, cytology became increasingly detached from its early reliance upon the light microscope. At the same time its links with cognate disciplines like microbiology, genetics, biochemistry, and molecular biology have become ever more intimate. Using techniques drawn from these sciences, cytologists have been able to provide fuller accounts of how the different parts of the cell perform their metabolic and reproductive functions.

STEPHEN JACYNA